**<u>İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY</u>**

# VECTOR CONTROL OF PMSM
# IN WASHING MACHINE APPLICATION

**M.Sc. Thesis by**
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**Programme : Control and Automation Engineering**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

# ÇAMAŞIR MAKİNESİ UYGULAMASINDA SMSM'NİN VEKTÖR KONTROLÜ

**YÜKSEK LİSANS TEZİ**

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## FOREWORD

Firstly, I would like to express my deep appreciation and thanks for my advisor. Without his guidance, support and patience on listening my endless complains I would not be here writing this study. Moreover, I would like to thank Dr. Latif TEZDUYAR, Günsu ALBAŞ and Kerem ERENAY and the staff of Arçelik A.Ş. Power Electronics Research and Development Department for their support and help throughout the studies. Without them, the experimental platform would be too hard to achieve. Lastly, I would like to thank my family, friends and Peter PARKER who supported me through tough times and all my life. This work is supported by ITU Institute of Science and Technology.

February 2011

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## ABBREVIATIONS

**AC** **:** Alternating Current
**BLDC** **:** Brushless Direct Current Motor
**CIM** **:** Vector Controlled Induction Motor
**DC** **:** Direct Current
**EMC** **:** Electromagnetic Compatibility
**EMF** **:** Electromotive Force
**EMI** **:** Electromagnetic Interference
**FOC** **:** Field Oriented Control
**MCU** **:** Microcontroller Unit
**MMF** **:** Magnetomotive Force
**NdFeB** **:** Neodymium Iron Boron
**PM** **:** Permanent Magnet
**PMAC** **:** Permanent Magnet AC Motor
**PMSM** **:** Permanent Magnet Synchronous Motor
**PWM** **:** Pulse Width Modulation
**UM** **:** Universal Motor

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**VECTOR CONTROL OF PMSM IN WASHING MACHINE APPLICATION**


**SUMMARY**

It could be stated that there is a recent trend in appliance industry towards more efficient and greener products. This trend is triggered by the recent energy regulations and concious customer profile. In order to produce energy-efficient appliances manifacturers are taking new steps towards innovative approaches and newly designed high-segment energy efficient products. These steps bring a need for high efficiency motors and sophisticated control algorithms when the washing machines are of concern. In order to choose a motor that is suitable for washing operation, in the scope of this thesis, firstly the washing machine operation and its speed and torque characteristics in different working cycles are introduced in first chapter. After the examination of the washing operation in second chapter, a brief comparison of the motor types that are currently used in mass production is made in third chapter. After the comparison and a brief information on each motor type, a suitable motor is chosen to be PMSM for an energy efficient washing machine.

In fourth chapter comparison of PMSM with other possible candidates for energy efficient washing machines is made and mathematical model of the PMSM is derived in three reference frames namely (a,b,c), ($\alpha$,$\beta$) and (d,q). With the mathematical model deriven the used control method is explained in the fifth chapter. It should be noted that throughout the studies, a prototype system is built for the control algorithm to be applied and executed on this prototype washing machine. All results concerning the performance are experimental results gathered from this prototype.

In sixth chapter an online adaptive tuning scheme that is used to tune the current PI controllers is introduced right after introducing the conventional empirically tuning method that is widely used in industry. The details of the tuning scheme is provided. After an introduction on the adaptive scheme, the optimization method which is the basis of the tuning operation is introduced and briefly explained. Nelder-Mead optimization method which is the basis of the tuning operation is

examined and its advantages along with its flaws are provided. The modifications made on the algorithm is introduced and finally in seventh chapter experimental results with and without using the optimization algorithm is provided.
Lastly in the eighth chapter the results of the study is discussed by making use of the evaluation of the experimental results and the theoretical information provided in the former chapters. With the deductions made, a brief future study course is introduced.

**ÇAMAŞIR MAKİNESİ UYGULAMASINDA SMSM’NİN VEKTÖR KONTROLÜ**

## ÖZET


Tüm diğer sektörlerde olduğu gibi beyaz eşya endüstrisinde de daha verimli ve deyişi yerindeyse yeşil olarak tabir edilen, daha az enerji sarf eden ve doğal kaynak tüketimi en azlanmış ürünlere doğru bir yönelim olduğu açıkça görülen bir gerçektir. Bu yöneliminde, son yıllarda öncelikle yurt dışında Avrupa ve Amerika kıtasında bulunan ülkelerle başlayan ve zamanla tüm dünyaya yayılarak herkes tarafından kabul gören enerji regulasyonlarının çok büyük payı vardır. Ayrıca, bu regülasyonlar ve gerçekleştirilen pozitif bilgilendirme ile oluşturulmuş olan duyarlı müşteri profilide söz konusu yönelimi tetiklemekte yardımcı olmuştur. Bu şartlar altında, endüstrinin doğal gelişimine ayak uydurarak daha verimli beyaz eşya üretmek isteyen üretici firmalar yenilikçi çözümlere ve yeni tasarlanmış üst-segment verimli ürünlere doğru adım atmaktadırlar. Bu adımlar atılırken, beyaz eşye ve çamaşır makinesi özelinde, yüksek verimli motorlara ve gelişmiş kontrol algoritmalarına gerek duyulmaktadır.

Gelişmiş kontrol algoritmalarının seri üretim ve beyaz eşyade uygulanması son 10 yıla kadar hem teknik hem de maliyet anlamında neredeyse imkansızdı. Son yıllarda gelişen yarı iletken teknolojisi, hem bu algoritmaların kurulacağı işlemcilerin kapasitesini arttırdı hem de bu söz konusu işlemci tüm devrelerinin fiyatlarında ciddi düşüşlere sebep oldu. Gelişen teknoloji ile daha ucuza, daha kapsamlı ve güçlü işlemcilerin üretilmeye başlaması, yüksek seviyeli kontrol işlemlerinin seri üretimde uygulanmasında önemli bir kilometre taşı olarak sayılabilir.

Çamaşır makinesi düşünüldüğünde kontrol algoritmalarının yanı sıra, SMSM olarak adlandırılan ve gerek bilimsel gerek de uygulamaya yönelik çevrelerce en verimli motor tipi olarak kabul edilen sabit mıknatıslı senkron motorların kullanılmasının yolu da, yine ekonomik sebeplere dayanmaktadır. Yaklaşık son 10 içerisinde bakır fiyatları artmakta olup, motor konstrüksiyonunda kullanılan güçlü mıknatısların fiyatları hızla düşüş göstermekteydi. Bu ekonomik değişim, seri üretimde SMSM’lerin kullanabilmesine olanak sağladı.

Yüksek verimli motorları ve gelişmiş kontrol algoritmaları ile evlerimize giren beyaz eşya ve tüketici elektroniği örnekleri, son kullanıcının imkanına uygun ev içi teknolojilerin iyileşmesi ve ilerlemesinin bir örneği sayılabilir.

Bu tez kapsamında, öncelikle, çamaşır makinesi uygulamasına genel bir giriş sağlanmış ve seri üretimde kullanılmakta olan çamaşır makinesi mekanik tarasımları incelenmiştir. Üstten doldurmalı ve önden doldurmalı çamaşır makineleri olarak ikiye ayrıldıktan sonra ise kullanılan güç aktarım tipleri de ikiye ayrılarak kayış-kasnak düzenekli ve doğrudan tahrikli olarak ikiye ayrılmıştır. Bu tez kapsamında, önden doldurmalı kayış-kasnak güç aktarımı yapısına sahip bir çamaşır makinesi seri üretime yönelik prototipi kurulmuş, gerekli deneyler bu prototip üzerinde gerçekleştirilip tüm diğer detaylar ise bu varsayımla gerçekleştirilmiştir.

İkinci bölümde, çamaşır uygulamasına uygun bir motor seçilmesine bir temel oluşturması açısından çamaşır uygulamasının hız ve moment karakteristikleri sunulmuşt, detaylı bir inceleme gerçekleştirilmiştir. Çamaşır uygulamasına ait çalışma koşulları farklı bölgelere ayrılmış ve bu ayırım gerçekleştirildikten sonra motor seçimini etkileyecek karakteristikleri gösterilmiştir. Motor seçimi söz konusu olduğunda, çamaşır makinelerinin hız ve yük karakteristikleri önemli olduğundan; uygulama bu karakteristiklerine göre yıkama, durulama, dağıtma ve sıkma olarak dört ana bölgeye ayrıldıktan sonra, hız ve yük karakteristikleri şekiller ve sözel anlatımla okuyucuya sunulmuştur.

Tezin ikinci bölümünde verilmiş olan çamaşır uygulamasının incelenmesinin ardından üçüncü bölümde, Bu bölümde, hali hazırda seri üretimdeki çamaşır makinelerinde kullanılmakta olan motorların yapıları, çalışma prensipleri, kullanımdaki avantaj ve dezavantajları incelenmiştir. Bu incelemelerin ardından ise kısa bir karşılaştırma yapılmış, yüksek verimli bir çamaşır makinesi tasarımında kullanılması hedeflenen motor tiplerine karar verilmiştir. Bu karşılaştırma ve sözü geçen her motor tipine ait kısa bilgilendirmeden sonra, yüksek verimli bir çamaşır makinesi için en uygun motor tipinin SMSM olduğu çıkarımı yapılmıştır.

Dördüncü bölümde, SMSM ile diğer olası adaylar olan kontrollü asenkron motor ve fırçasız doğru akım motoru arasında gerçekleştirilmiş detaylı bir karşılaştırmanın ardından, SMSM’ye ait matematik model (a,b,c), (α,β) ve (d,q) eksenleri olmak üzere üç referans ekseninde çıkarılmıştır. Bu detaylı matematik model incelemesi, beşinci bölümde verilen ve prototipte kullanılan kontrol metoduna temel sunması açısından yapılmıştır. Kullanılan kontrol metodu, vektör kontrol veya alan yönlendirmeli kontrol olarak anılan motor modeline dayanan bir kontrol metodudur. Bu kontrol metoduna ait, çalışma koşulları, sensörsüz çalışma detayları, tahmin yapılarının genişletişmiş açıklamasının ardından kritik kontrol bölgeleri incelenmiş ve kullanılan işlemci yapısındaki kontrol işleminin özeti anlatılmıştır. Dikkate alınması gereken bir nokta, bu çalışma sürecinde prototip bir çamaşır makinesi edinilmiş ve bu makine üzerinde kontrol algoritması çalıştırılarak deneysel sonuçlar alınmıştır.

Tezin altıncı bölümünde ise, akım PI kontrolörlerinin detayı okuyucuya sunulmuştur. Endüstride kullanılmakta olan kontrolör ayar teknikleri anlatılmış ve tez dahilinde bu ayarlama için kullanılan uyarlamalı bir algoritması açıklanmıştır. Endüstride sıklıkla kullanılmakta olan geleneksel deneysel ayar yöntemine, ve bu yöntemin getirdiği problemlere değinilmiştir. Uyarlamalı yapının kısa bir tanıtımından sonra bu yapıya temel oluşturan optimizasyon algoritması olan Nelder-Mead algoritması tanıtılmış; avantajları ve kusurları tartışılmıştır. Bu optimizasyon algoritması üzerinde uygulamaya özel gerçekleştirilen değişiklikler de yine altıncı bölüm kapsamında incelenmiştir.

Bütün bu incelemelerin ardından, yedinci bölüm kapsamında, prototip üzerinde kurulan kontrol sistemi ve hem deneysel hem de uyarlamalı kontrol algoritmalarına dair deney sonuçları verilmiştir. Söz konusu deneyler hem yıkama hem sıkma bölgelerinde, boş ve yüklü tamburlar için ayrı ayrı, deneysel ve uyarlamalı kontrol algoritmaları için gerçekleştirilmiş, ilişkili veri sonuçları da bu bölüm içerisinde grafiksel olarak okuyucunun takdirine sunulmuştur.

Yedinci bölüm tezin amacı ve sonuçlarını içeren ilk bölümdür ve deney sonuçlarını içermektedir. Tezin bölümü olan sekizinci bölümde ise, çalışmanın sonuçları, gerçekleştirilen deneylerden alınan sonuçlar ve önceki bölümlerde incelenen teorik alt yapının ışığında tartışılmıştır. Bu tartışmalar sonucunda, algoritmanın kullanılması sırasında sistemde herhangi bir arıza gerçekleşmediği, algoritmanın genel hafıza gereksiniminin mevcut boş hafızayı aşmadığı ve dolayısıyla uygulanabilir olduğu görülmüştür. Ayrıca, yedinci bölümde sunulan deneysel ve uyarlamalı kontrol edilen deney sonuçları arasında yapılan karşılaştırmalara dayanarak, uyarlamalı kontrol kullanılması ile belirgin bir iyileşme gözlendiği, özellikle yüksek hızlarda ölçümdeki harmoiklerin giderildiği sonucuna varılmıştır. Görülmüştür ki, kullanılan algoritma sistem parametrelerindeki ufak değişikliklere bile çabukça cevap vererek dayanımlı bir kontrol sağlamaktadır. Bu bilgiler ışığında, yine tez kapsamında ve son bölümde, gelecek çalışmalar için kısa bir yol haritası çizilmiştir.

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# 1. INTRODUCTION

In modern houses washing clothes means putting them in the washing machine, putting sufficient amount of detergent and pressing a button. However, before automatic washing machines were invented this task required great amount of time and physical effort. At some point where people noticed they should wash their clothes to maintain daily hygiene, they used streams. As the washing machines evolved, this task started to became less time consuming but it was not less physical effort demanding until the use of electric motors as drives. The evolution of the washing machines as a domestic technological product made its peak after the automatic washing machines were introduced to the market. Following this milestone in the history of the washing machines, the development of them was mainly due to the concern of improving the customer satisfaction.

When customer satisfaction is of concern, one of the most important fields open to improvement is to get the washing quality better. Using better electrical motors with better performance has a big effect on this. The second field that is open to improvement is to ensure that the audible noise level is not at a disturbing magnitude. This can also be improved by having washing machines equip better types of motors with less noise level, which is controlled by a control algorithm that reduces commutation noises, but can also be improved by changing the drum design. Apart from these fields, maybe the most important one both from the manufacturer's and customer's point of view, is the cost of the appliance. This is highly dependent on the system's total cost, which is also highly dependent on the motor's and motor control electronics' cost.

It can be easily noticed that the motor equipped in a washing machine is an integral part of the system and a big factor for determining the performance, customer satisfaction and cost. That is why the motor should be chosen carefully, especially when designing high-end washing machines. The choice of the motor can only be done after having a good understanding of the washing operation, its characteristics, and requirements.

When the motor choice is of concern, one should know what kind of mechanical design the washing machine will have. There are typically two mechanical designs used in today’s market: top loading and front-loading washing machines. In top loading washing machines, motor is typically placed right under the drum, rotor rotation axis being vertical similar to drum rotation axis. Nevertheless, in top loading washing machines since there can be no tumbling action due to the gravitational forces of the laundry, there should be agitation, which is also powered by the motor. This makes them less power efficient than front loading ones, which can make use of the gravitational forces due to having horizontal drums. An example for a top loading washing machine is shown in Figure 1.

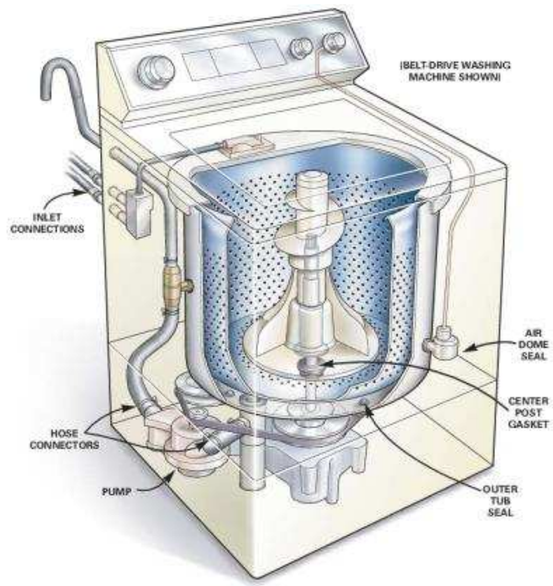


**Figure 1:** An example design of a top-loading washing machine.

In front loading washing machines, there are again two mechanical designs, horizontal placed drums and tilted drums. The operational details are similar and the tilted design of the drum does not particularly affect the motor choice. However, when front loading washing machines are of concern one can say that they are more power efficient especially in wash cycle. Because they can make use of the gravitational forces and do not need extra power to maintain agitation. In the scope of this thesis, front loading washing machines will be of concern. An example design of a front loading washing machine is given in Figure 2.

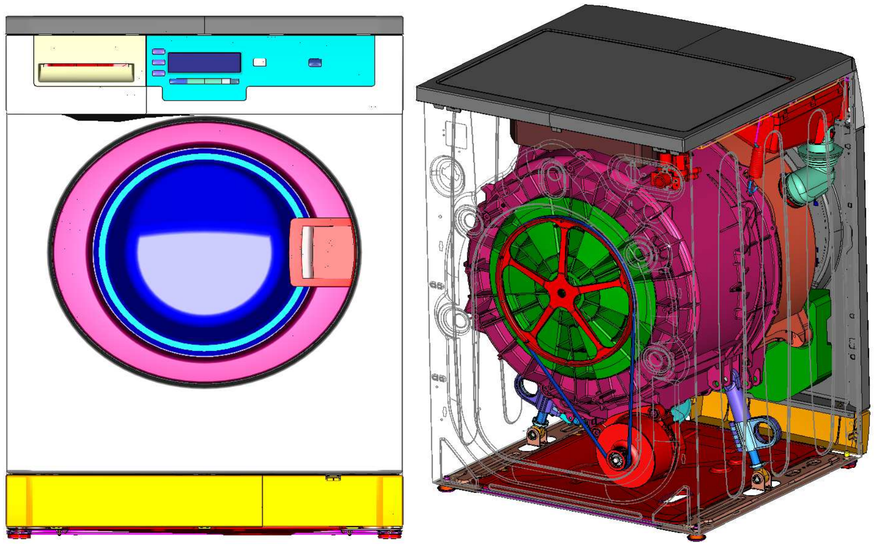

**Figure 2:** An example for mechanical design of a front loading washing machine.

As for drive types, there are also two widely used options. For front loading washing machines, the most common drive system is the belt drive system, where the motor is connected to the drum using a belt. Due to the use of belt, the speed of motor and speed of drum is not equal in these kinds of drive systems. This brings about ease with slow speeds in wash cycle, but it also has a disadvantage in high speeds. Because of the belt pulley ratio, the motor speed in spin dry cycle can reach 20000 rpm, which definitely means field-weakening region. Thus, the choice of the motor for belt drive systems is critical especially in terms of field weakening capacity and performance of spin dry cycle speed region. The second and recently popularity gaining type of drive system used in front loading washing machines is direct drive system. In this type of drive system since there is no belt ratio to take into consideration, the drum's speed and the motor's speed is equal. This ensures better performance when the spin-dry speed values are of concern. The downfall of the direct drive systems is at wash cycle speeds, which means steady operation in low speed values such as 50 rpm when electric motors are considered. Direct drive type of drive system is still open to development but can also be found in washing machines in the market. In the scope of this thesis, belt drive systems will be of concern.

## 2. WASHING OPERATION and WORKING CYCLES

Washing operation, shown in Figure 3 can be divided in to four main cycles. The first cycle is the wash cycle where the cleaning is done by tumbling the laundry with water and cleaning agents. The second cycle is rinsing cycle, which is similar to wash cycle and is done in order to rinse the laundry, clean all the detergent and cleaning agents used with water. The third cycle, which considerably lasts shorter than all of the cycles, is the distribution cycle. In this cycle, the laundry is tumbled at a moderate speed without water in order to reduce the unbalanced load that might occur in the last operation cycle which is spin drying. Spin-drying is the last cycle and usually lasts around 10 to 20 minutes.  It makes use of the centrifugal forces and extracts the water absorbed by the laundry in wash and rinse cycles. These cycles will be examined in detail below in terms of operation characteristics, power requirements, speed, and torque characteristics.

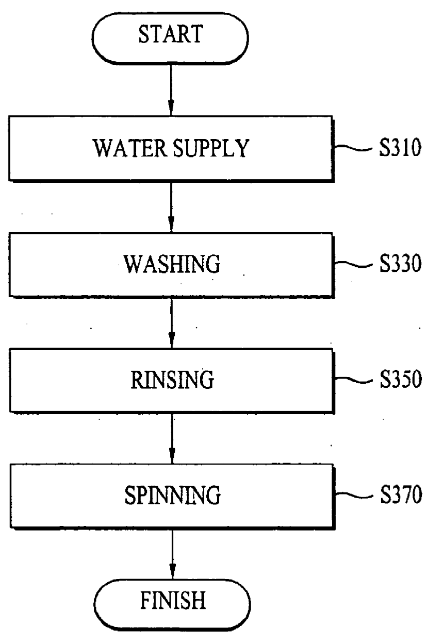


**Figure 3:** Flowchart of washing operation.

## 2.1 Wash Cycle

Wash cycle is the main cycle of the washing operation and it is also the longest operation cycle in terms of operation time. The clothes are tumbled at a considerably low speed with cleaning agents and water in order to provide the cleaning operation during the wash cycle. This cycle usually lasts between 30 to 60 minutes, which consists of constant tumbling operation. To ensure the cleaning of the laundry the drum is spinned at 40 to 80 rpm [1] at an average speed of 50 to 60 rpm in order to provide effective cleaning [2].

In this cycle, firstly the water is pumped in to the drum through the cleaning agent compartment in order to mix the water and the detergent. This causes a considerably big load for the first start up of the motor. This high load value at the start up which is caused by the laundry placed at the bottom of the drum falls down as the drum moves. Torque characteristics of the wash cycle are shown in Figure 4. It is common for fluctuations in the torque characteristics to be observed during wash cycle. These fluctuations are mostly caused by the tumbling operation.

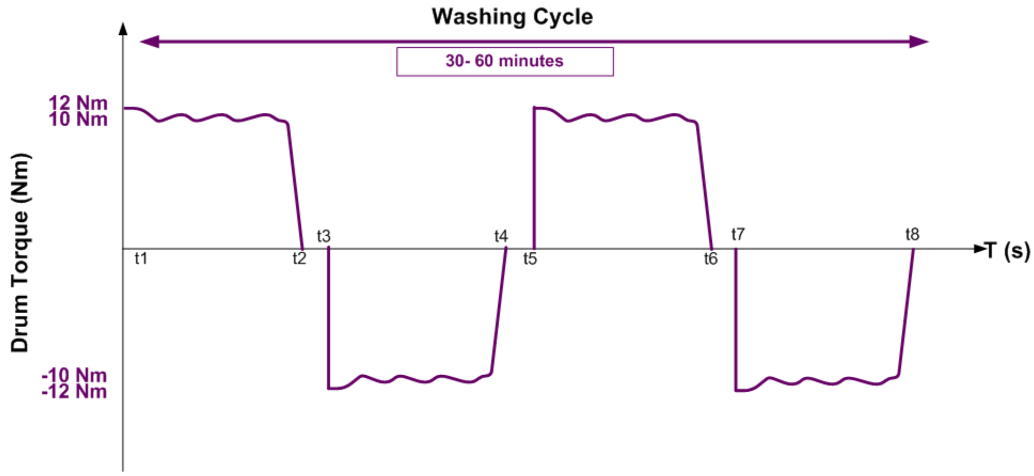


**Figure 4:** Torque characteristics of washing operation in wash cycle.

To wash the laundry, the drum is spinned at lower speeds for the clothes to tumble using their own masses. The diagram of the drum and the laundry is shown in Figure 5 and Figure 6. Typically the laundry would stick to the drum until the centrifugal force, Fc is equal to the gravitational force's component in the same axis F=mgsin(θ). At a critical angle, θ, which is also the drum's position, these forces become equal and the laundry, falls from the top of the drum to the bottom, which causes a big difference in the load. Angle θ is highly dependent on the drum radius.

That is why the drum design also has effect on the performance of the washing operation.

From Figure 5 and Figure 6. it can also be seen that the laundry will mostly never pass the angle $\theta = 90°$, causing a consecutive high load after the laundry falls to the base of drum, which is a little lower than the one seen at startup because the drums are designed that way in order to simulate how people used to wash clothes in streams by pounding them on rocks. The phenomenon of tumbling is the reason of the fluctuations in the load characteristics. Washing operation continues for 30 to 60 minutes until wash operation cycle ends. Because of the big load consisting laundry and water and these fluctuations, most of the heating on the motor occurs in wash cycle operation due to the high current needed to drive the motor as a consequence of high torque. As can be seen, the laundry load is highly nonlinear and stochastic due to the unattached nature. Therefore, it can be said that one of the problematic parts of a washing operation is the laundry load's behavior characteristics, which may become highly chaotic.

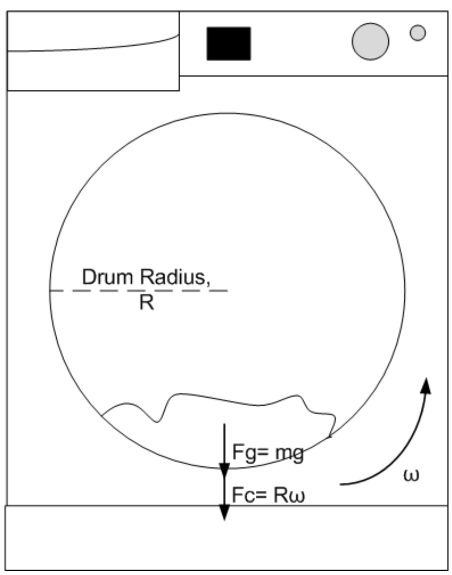


**Figure 5:** Laundry at the bottom of the drum.

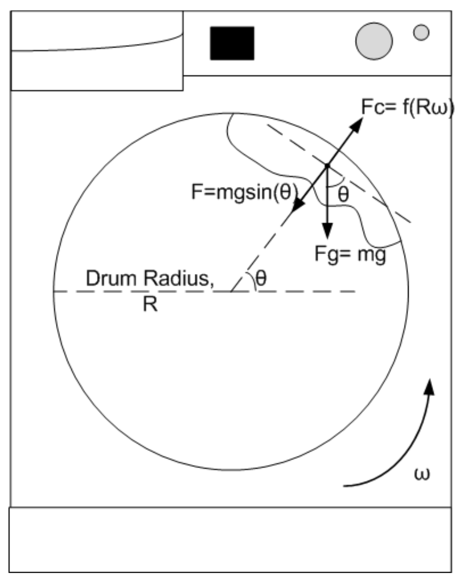


**Figure 6:** Laundry at the critical angle.

As for speed characteristics of wash operation, as said before the drum is spinned at an average speed of 50 rpm. However, the fluctuations in torque also reflect on the speed characteristics. Speed characteristics are shown in Figure 7. Figure clearly shows the fluctuations that can be observed during wash cycle. These are highly due to the torque fluctuations. The speed range might be from 40 rpm to 60 rpm during wash cycle with a reference speed of 50 rpm. This means constant speed error, and requires highly dynamic control algorithms with a good dynamic response.

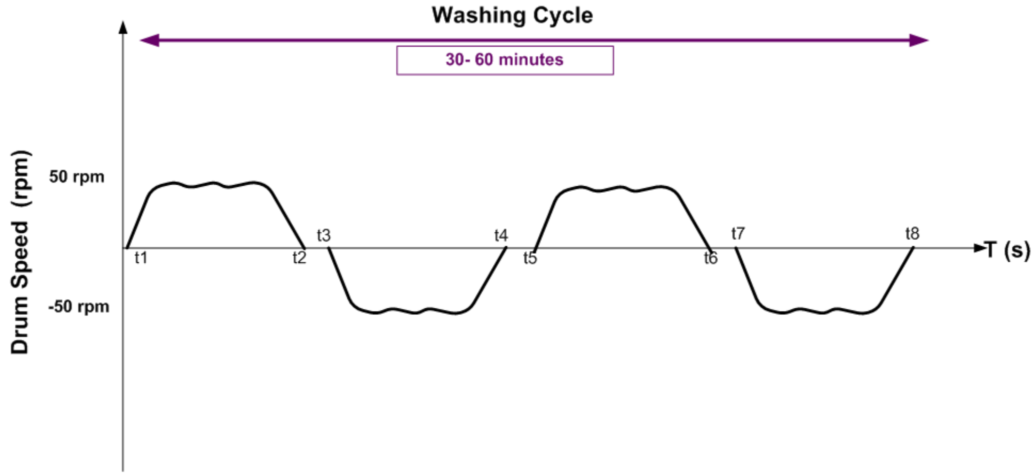


**Figure 7: S**peed Characteristics of washing operation in wash cycle.

### 2.2 Rinsing Cycle

Rinsing cycle is typically a wash cycle with more water. Firstly, the excess water with detergent and cleaning agents is disposed. After the disposal of the foamy water, fresh water is pumped in to drum and the laundry is tumbled with this water in order to get rid of the cleaning agents. This operation is done multiple times in order to ensure the rinsing operation.

Due to water amount being larger, the load is simply bigger. But, that does not resolve the issue of fluctuations caused by tumbling. Because of more water, laundry tends to behave more linearly than in wash cycle but there still is place for them to fall. This results with less fluctuations in rinsing cycle than in wash cycle but it cannot be said that there is none. Torque characteristics are shown in Figure 8.

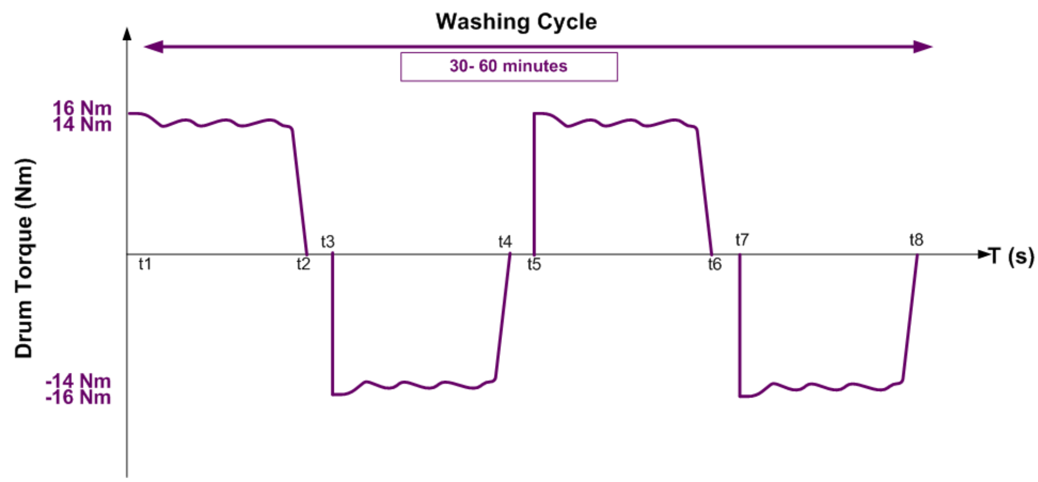


**Figure 8:** Torque characteristics of washing operation in rinsing cycle.

Speed characteristics of rinsing cycle also does not differ much from wash cycle's speed characteristics. The most significant difference is that in rinsing cycle the operation speed is lower than of wash cycle's. This brings about more problems in terms of low speed operation region of motors especially with high loads. Speed characteristics of the rinsing cycle are given in Figure 9.

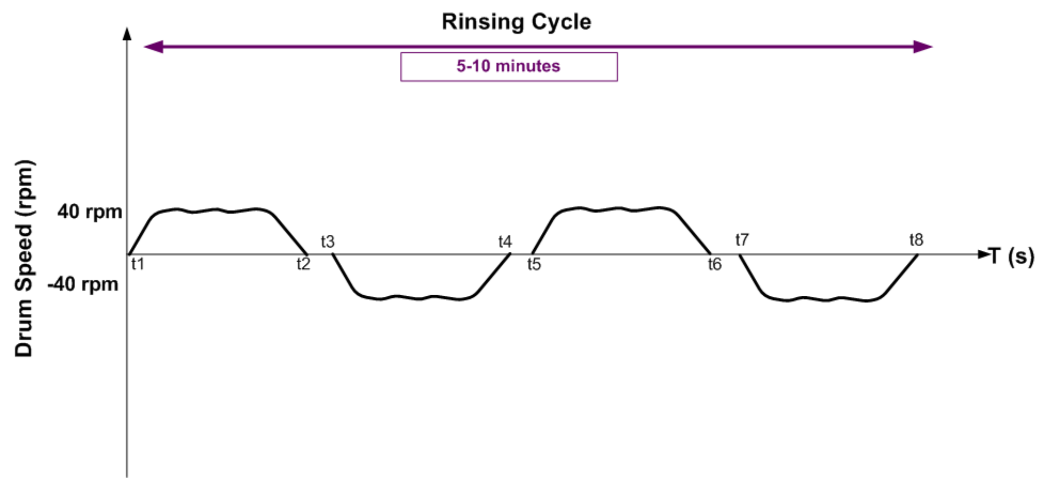


**Figure 9:** Speed characteristics of washing operation in rinsing cycle.

### 2.3 Distribution Cycle

Distribution cycle can also be introduced as preparation cycle of spin dry cycle. Laundry usually clumps in washing and rinsing cycles with the help of water and because of tumbling operation. The reason why the clothes stick together and become a one big lump of load is this, which is not desired when the motor is spinned at higher speeds since this cloth lump, would stick to the drum surface due to the centrifugal forces and cause an unbalanced load. Because of this, distribution cycle is operated right before spin dry cycle. In this working region, firstly all of the excess water that is not absorbed by laundry in wash and rinsing cycles is dispensed. After that, the drum is rotated at 100 rpm in order to distribute the laundry that is possibly clumped after the washing and rinsing cycles. This cycle lasts shorter than all of the washing operation cycles. The duration of the distribution cycle is about 1 to 3 minutes.

The load characteristics of distribution cycle are considerably different from of wash and rinsing cycles. Because the excess water is drained, the load becomes smaller. In distribution cycle, the load is just the laundry, which has absorbed the water used in wash and rinsing cycles. Because the drum speed is higher than in wash and rinsing cycles no tumbling, operation is observed in distributing cycle except when the drum stops. Even though there still are fluctuations in load but this time, it is highly due to the unbalanced load occurring because of the clumped clothes adhering to the drum surface and not due to the tumbling of the laundry. The torque characteristics of a distribution cycle are shown in Figure 10. As can be seen the typical behavior of laundry load at the start up can also observed in distribution cycle. Nevertheless, this time the load amount is considerably smaller. In addition, there are fluctuations observed too.

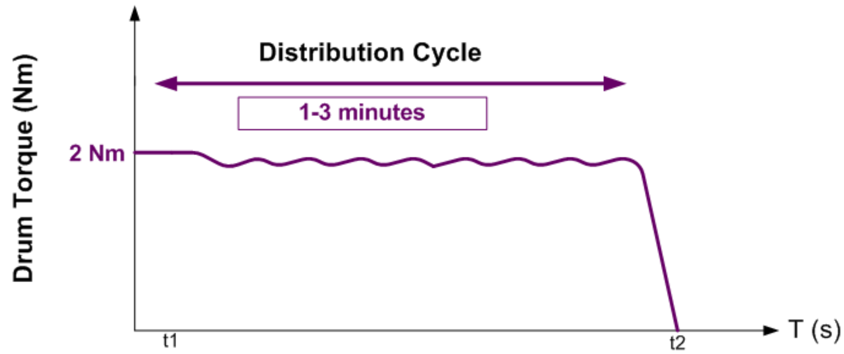


**Figure 10:** Torque characteristics of washing operation in distribution cycle.

The speed characteristics of distribution cycle can be considered one of the less problematic regions of the washing operation. Due to the applicable speed region, for all kinds of motors of distribution cycle this operation region has less problematic characteristics than any of the other regions. Typically, drum is rotated at 100 rpm causing the laundry stick to the drum surface and is distributed by the constant rotation motion. The speed characteristics are shown in Figure 11.

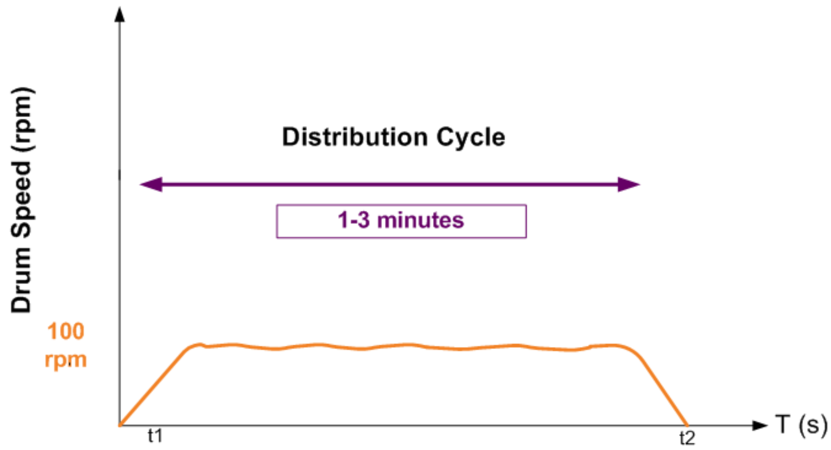


**Figure 11:** Speed characteristics of washing operation in distribution cycle.

### 2.4 Spin Dry Cycle

This cycle is mostly known for a phenomenon occurring during the operation: unbalanced load. Unbalanced load basically is the load occurring at one point of the drum caused by clothes adhering to the drum surface, which was not distributed in the distribution cycle. Even though the distribution cycle is operated in every wash operation, unbalanced load occurring is a phenomenon that is common to observe. Distribution cycle simply reduces the amount of the unbalanced load occurring. Even though the average load amount is smaller in spin dry cycle because the excess water is dispensed, unbalanced load causes significant fluctuations in torque profile of spin dry cycle. The load characteristics of spin-dry cycle is shown in Figure 12.

It can be stated that the spin-dry cycle is the most problematic working cycle in a whole washing operation. This is because the spin dry cycle, especially in modern washing machines, requires the drum spinning at really high speeds. Most modern high-end washing machines have final spin dry operation at 1400 rpm drum speed. Recently developed rare examples that can reach up to 1600 and 1800 rpm drum speeds can be seen in the market. This means unless the washing machine is equipped with a direct drive motor, it will require the motor to spin in field weakening region to reach these speeds. Considering the length of the spin dry cycle, which can last around 5 to 20 minutes this operation in field weakening region, will cause heating especially in motor control electronics, which makes it essential for the control to be made accordingly. The speed characteristics of spin-dry cycle is shown in Figure 13.

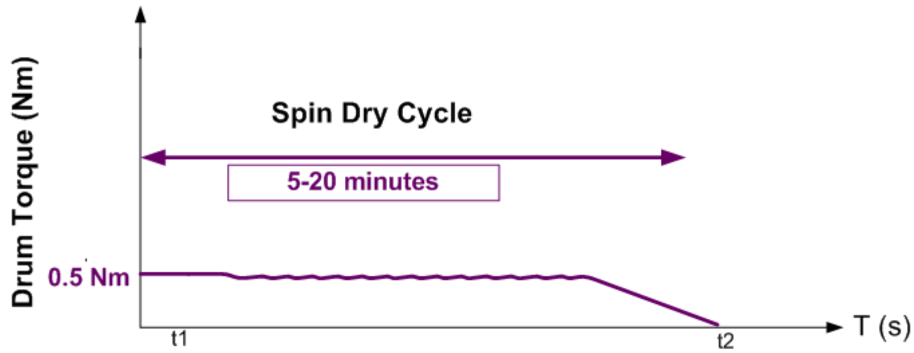


**Figure 12:** Torque characteristics of washing operation in spin dry cycle.

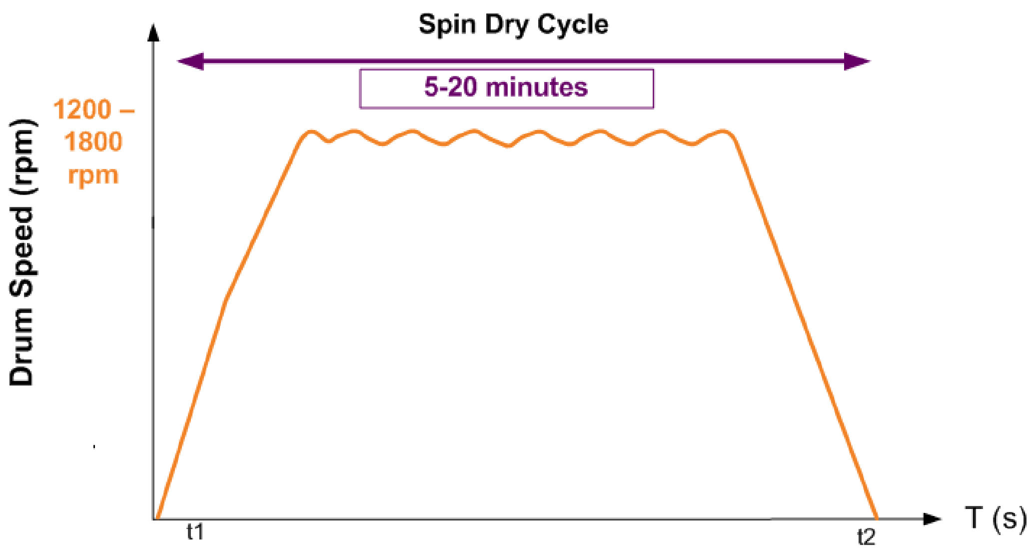


**Figure 13:** Speed characteristics of washing operation in spin dry cycle.

# 3. ELECTRICAL MOTORS USED IN WASHING MACHINES

When choosing an electrical motor for a specific operation, one must particularly deal with some aspects of the motor and the operation itself. In terms of motor choice for washing operation, four criterions can be highlighted. These criterions are technical characteristics, reliability, cost, and application convenience.

First criterion mentioned being the technical characteristics of the motor is what limits the possibilities most. What designers expect from a motor to be used in washing machines in terms of technical characteristics can be listed as; a high power-volume ratio and torque volume ratio, a wide speed range, to be able to operate in two directions, acceleration control and sensitivity. A high power-volume and torque-volume ratio is expected because of the fact that washing machines have limited space for a motor and both power and the torque level of the motor is what affects the amount of laundry that can be loaded in a washing machine. As a marketing strategy, higher capacity for laundry load is always appreciated in smaller washing machines. Also smaller in size means smaller windings and smaller motor laminations, which brings considerable cost reduction. Wide speed range, on the other hand, being a part of the marketing strategy, is always appreciated in order to create the ability to have higher final spin speed. The motor used in a washing machine is expected to rotate in both clockwise and counter-clockwise directions in order to provide a satisfying tumbling operation in wash cycle; this means the motor should be able to operate in both quadrants of the motor operation. Lastly, the acceleration control of the motor should be robust and motor should not be sensitive to external electrical noises.

Second criterion being reliability itself is a main research area. All motors used in end-user products are expected to be reliable. The details of this criterion are not within the scope of the thesis. But the main idea is to have the motor and motor control electronics to be reliable in order to have longer lifetime and reduce the faults and product malfunctions.

The third criterion is the cost, being the most important criterion of all from the manufacturer’s point of view. The manufacturers always appreciate lower cost, but they always expect better technical characteristics. Thus, this criterion cannot be examined without being concerned with the technical characteristics of the motor. The motor that is going to be used in a washing machine is expected to provide all the necessary conditions for a washing operation and still be cost effective.

The last criterion for choosing a motor is the application convenience. This criterion can be explained as the comfort level for the end-user, which can be categorized as noise level, heating, vibration level of the motor and lastly the size. From customer’s point of view, people would not want to have washing machines that have too high level of acoustic noise. Because of this reason, the noise level of the motor is important when choosing a motor for a washing machine. The heating level of the motor can be important in higher speeds because of the fact that motor parameters will change as the temperature rises, so there is always a chance of saturating the motor or demagnetizing the magnets. The vibration level of the motor is a critical criterion in terms of design. If the motor is not designed or chosen properly, the vibration of the motor and the washing machine itself can become synchronized in the motor’s resonance frequency, which causes a disturbing sound of magnetic origin.

The main types of motors that are used in modern washing machines can be listed as below.

- Induction machines

- Universal motors

- Permanent magnet AC motors

The detailed examination of motor types will be given below. In this part motors’ operating principles, equivalent circuits, torque-speed characteristics, advantages and disadvantages in terms of washing operation will be provided and consequently a brief comparison will be made.

### 3.1 Three Phase Induction Machines

Induction machines are the most common types of motors used both in industry and specialized application in wide range of power ratings. One reason for the popularity of cage-type induction motors is that they are cheap and rugged [11]. However, their efficiency is somewhat inferior because of high copper losses. Since they have a settled technology, they are still in trend even to this day even though they bring about many problems to some particular systems. In addition, if they are not controlled adequately, they cannot provide a full washing operation in terms of both speed and load.

#### 3.1.1 Operating principle

Basic structure of a 3-phase induction machine has poly phase windings on both stator and rotor. Typically, the stator winding which is also called the field winding is connected to the AC source and the rotor winding which is also called the armature winding is short circuited [12]. Poly phase windings on stator carrying AC currents create a rotating magnetic field. This rotating magnetic field induces an AC current in the poly phase rotor windings situated in this rotating magnetic field according to Faraday’s Law [13]. Since the stator has an AC current flowing, it is already an electromagnet in behavior. After there is an induced current in rotor windings, the rotor behaves also as an electromagnet. From the interaction of these electromagnets, rotor starts to rotate. However, if the rotor’s spinning frequency is not smaller than the rotating magnetic field’s frequency, which is also called the synchronous frequency, there cannot be any current induced on rotor windings. This difference between the rotor’s frequency and synchronous frequency is also called the slip. Without this speed difference between the rotor field’s frequency and rotor itself, it is not possible to operate the induction machine [12]. The operation is illustrated for a two-pole induction machine in Figure 14.

An induction motor can produce a rotating motion with the sole existence of slip. The windings of rotor will simply try to catch the frequency of the rotating magnetic field created by stator windings thus inducing a voltage, which produces a current because of the fact that conductors are short, circuited. Thus, creating a rotating motion.

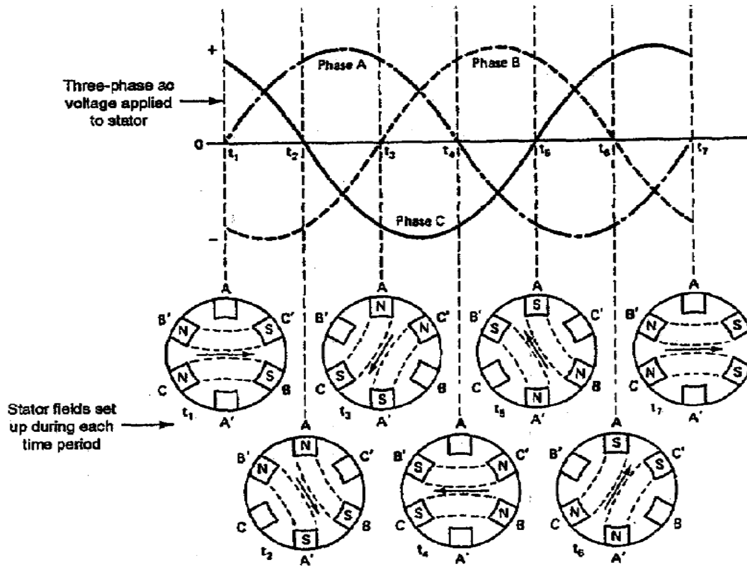


**Figure 14:** Operation principle of an IM.

### 3.1.2 Equivalent circuit

Motor equations can be derived from the equivalent circuit so, in order to understand the speed control of the induction machine, it is highly advantageous to examine the equivalent circuit of the motor beforehand.

Before giving the equivalent circuit, it should be noted that all quantities given are in the stator reference frame and the circuit model should be examined keeping that in mind. In Figure 15 the equivalent circuit of an induction machine for one phase winding is given.

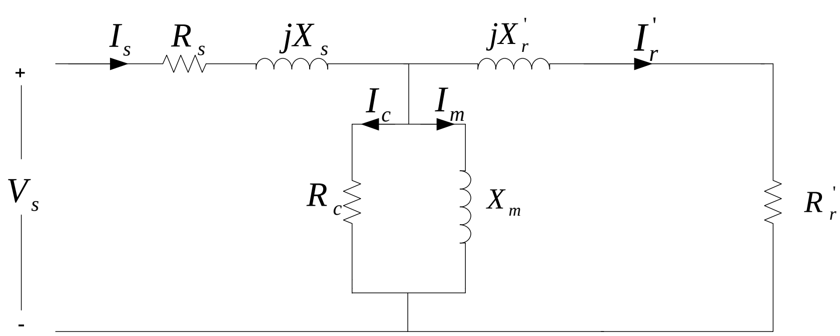

**Figure 15:** Equivalent circuit of an induction machine.

The quantities shown in Figure 15 are explained below.

$V_s$ : Supply voltage

$I_s$ : Stator current

$I_c$ : Copper loss current

$I_m$: Magnetization current

$I_r'$ : Rotor current in stator reference frame

$R_s$ : Stator winding resistance

$R_r'$ : Rotor winding resistance in stator reference frame

$R_c$ : Core loss resistance

$jX_s$: Stator leakage impedence

$jX_r'$: Rotor leakage impedence in stator reference frame

$X_m$: Stator magnetizing reactance

### 3.1.3 Torque-speed characteristics

When one chooses or designs a motor for a specific operation, rather than its mathematical model, cost, reliability or the control method, the most important feature that affects the choice or the design is usually torque-speed characteristics of the motor. In Figure 16, torque speed characteristics of an induction machine for constant stator voltage and frequency is given. From the various regions of torque speed characteristics of induction machine, the region between standstill speed and synchronous speed is the most important and most widely used one [14].

As can be seen from Figure 16 the torque of the motor greatly varies with the variation of speed, in other words the variation of the slip. The startup torque, $T_s$ of an induction machine is lower than its maximum torque. This is not a desirable feature in terms of washing process since the maximum torque will occur at the start up. Also, there are two important speed values that are needed to be known for an induction machine in order to evaluate the appropriateness of the motor type. First speed value is the critical speed value, on which the maximum torque can be produced from the induction machine. In the operation region with speed values greater than the critical speed value $n_c$, the torque that can be produced by the induction machine rapidly falls, and finally becomes zero at maximum speed, which is also called synchronous speed $n_s$. This feature is acceptable in terms of washing operation since, in spin dry cycle, which uses the high-speed operation region of an induction machine, the load torque is much smaller than it is in wash cycle.

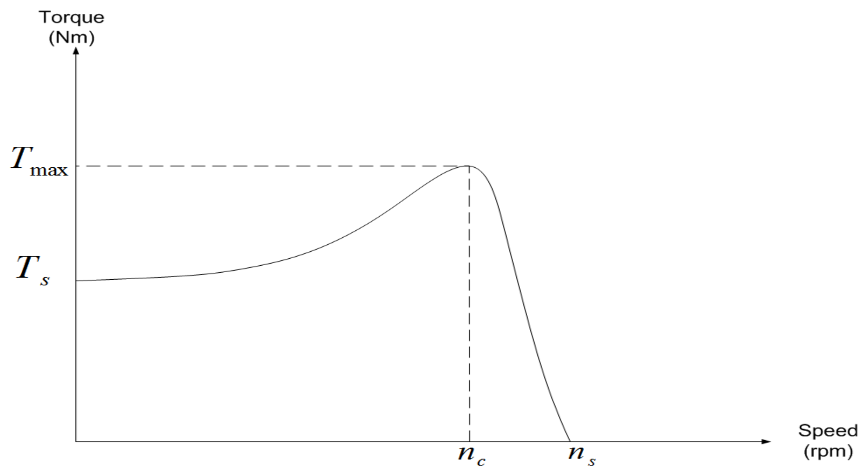


**Figure 16:** Torque speed characteristic of an induction machine.

### 3.1.4 Advantages and disadvantages

Known for their easy assembly and well-known control techniques such as scalar control, induction motors in other words three phase asynchronous motors were one of the most popular motor types used in commercial products. Having advantages such as high reliability, long lifetime, lowest cost, wide speed range, smaller size, smooth torque development, high controllability, and easy field weakening kept them under the spotlight for years. But disadvantages such as high losses, problems in low speeds, and higher cost in control circuit compared to universal motor controllers had them leave their spot in commercial use and left their place to universal motors. The general advantages and disadvantages of an induction motor are listed in below.

#### 3.1.4.1 General advantageous properties of an induction machine

- Easy assembly
- High reliability
- Long lifetime
- Lowest cost
- Wide speed range
- Smaller size
- Smooth torque development
- High controllability
- Easy field weakening operation

#### 3.1.4.2 General disadvantageous properties of an induction machine

- High losses
- Higher cost in control circuit
- Problematic operation in low speed region
- Heating problems because of high losses specially in low speed region
- High inertia
- Bearing problems in high speeds

## 3.2 Universal Motors

Universal motor can be simply defined as an alternating current machine of which's armature and field windings are connected in series. In its simplest case, it is also possible to describe universal motors as motors, which can be supplied with both AC and DC voltages, hence called universal. Even though they can also be supplied with AC power, they are mostly classified under DC motor sections because of the fact that their structure is similar to DC motors. Since the domestic line voltage is single phase AC, universal motors are widely used in domestic applications. For example, small universal motors are used in applications where weights is a critical issue such as vacuum cleaners, kitchen appliances, and portable tools, and they usually operate at high speeds which ranges from 1500 rpm to 15000 rpm [15]. Another factor for universal motors to be used widely is the ease of speed control, which can be done with a simple AC chopper circuit [16].

### 3.2.1 Operating principle

Since universal motors can be supplied with both AC and DC power supplies, their operating principle can also be examined in working conditions. In washing machines, the supply voltage is the AC line voltage, so in the scope of this thesis, operating principle of universal motor with AC supply voltage will be examined.

Universal motors mostly behave as an AC series machines with collectors. Since the armature and field windings are connected in series, when the motor is supplied, both stator and rotor windings will be supplied. The current creates a magnetic field in the pole windings and the current in the rotor windings reacts to this field and starts to move. Since the alternating current changes its direction periodically as a result of being sinusoidal, the torque direction will be constant as the rotor spins.

### 3.2.2 Equivalent circuit

In Figure 17, the equivalent circuit for a universal motor is given. As can also be seen from the equivalent circuit, the armature and the field windings are connected in series.

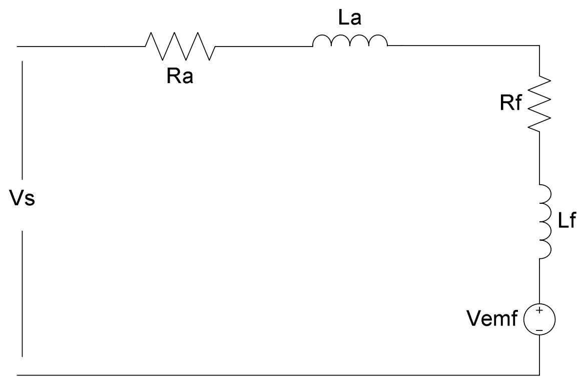


**Figure 17:** Equivalent circuit of a universal motor.

The quantities given in the equivalent circuit is listed below.

$V_s$ : Supply voltage, AC

$R_a$: Armature resistance

$L_a$: Armature inductance

$R_f$: Field winding resistance

$L_f$: Field winding inductance

$V_{emf}$: Back EMF voltage

### 3.2.3 Torque-speed characteristics

Torque speed characteristics of the universal motor are given in Figure 18. As can be seen from the figure, the torque at the start up and low speed region has the highest values. As the motor goes into the higher speed regions, the torque production rapidly falls. This characteristic is usually not wanted especially in applications, which require constant torque. However, for washing machine operation, it is more suitable than of induction machine’s working characteristics. Since the washing machine has the biggest load at the start up and low speed regions, universal motor would be able to provide the torque needed to tumble the laundry with motors of lower power ratings. Moreover, in high-speed regions, the laundry load has the smallest amount. This property of the wash load also fits to the characteristics of universal motors.

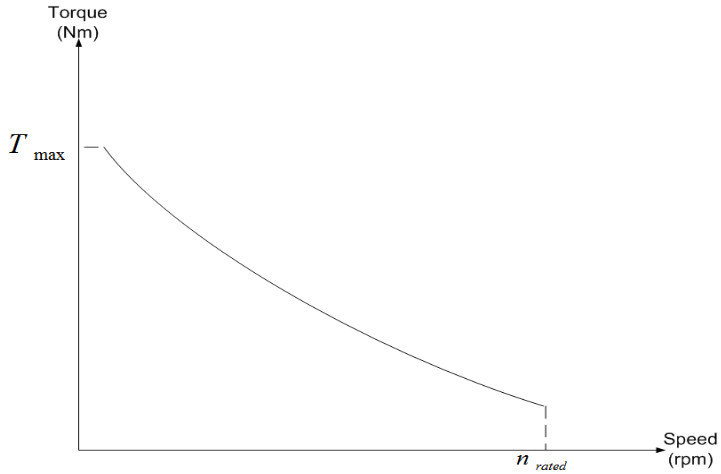


**Figure 18:** Torque speed characteristics of a universal motor.

### 3.2.4 Advantages and disadvantages

Another popular type of motor used in commercial products is universal motors (AC/DC). Because of their advantages such as their well-known and settled technology, being produced in high volumes, thus being cheaper, low cost control electronic, easy observation of EMC standards etc. Universal motors are still being used in high volume commercial products such as washing machines. Nevertheless, comparing to induction motors and brushless motors their lifetime is shorter because of commutator and brushes. They have higher sound power level, which is not desired in commercial products. Also, the brushes cause irritated disturbances at high speeds. Above all, they have lower energy saving performance. The general advantages and disadvantages of universal motors are listed below.

#### 3.2.4.1 General advantageous properties of an universal motor:

- Settled technology
- Simple control electronics which is an AC chopper circuit
- Can provide high torques in low speed region
- The rotation direction control can be done with a simple contactor
- Wide operational speed range

#### 3.2.4.2 General disadvantageous properties of an universal motor:

- Complicated motor structure
- Has collector/brush system
- Requires maintenance
- High noise level

- Low torque/inertia level
- Nonlinear characteristics
- Higher cost compared to induction machine
- Need for a feedback unit for speed control

### 3.3 Permanent Magnet Motors

Recent developments in rare-earth Permanent magnet (PM) materials and power electronics have opened new prospects on the design, construction and application of PM motors [17]. It has been always known that permanent magnet motors have highest efficiency levels, but they were at the same time expensive types of motors. Recently, due to the increase in the prices of copper and decrease in the prices of rare earth magnetic materials such as NdFeB, the popularity of PM motors are rapidly rising.

The PMAC motors are classified based on the wave shape of their induced EMF, i.e., sinusoidal and trapezoidal. The sinusoidal type is known as PMSM and the trapezoidal type are called PM DC brushless machine (BLDC) [8]. Therefore, we can say that PM motors can be divided mainly into two categories. The first motor type is the brushless DC motor and the second is the permanent magnet synchronous motor. Even though they are both three phase AC supplied permanent magnet motors, which look pretty similar, their constructional details and working principles greatly vary.

#### 3.3.1 Operating principle

Operating principle of both BLDC and PMSM are similar and simple. The stator windings are supplied from a three-phase AC source. In a manner that one phase winding is positively energized, second phase is negatively and the third phase is non-energized [18]. As the stationary three phase windings having AC currents produce a magnetic field, the magnets mounted on or in the rotor, reacts to this magnetic field and the rotor starts to rotate with the help of magnetic forces occurring between the permanent magnets and the magnetic field created on the stator windings. Nevertheless, in order to keep the rotor of a BLDC rotating, a special commutation sequence named six-step commutation is used. This commutation sequence is shown in Figure 19.

As for PMSM control, it is also possible to used six step commutation sequence. Moreover, for an even better performance control scheme sinusoidal commutation sequences such as sinusoidal six-step commutation can also be used. Since it is not in the scope of the thesis, the details will not be given here.

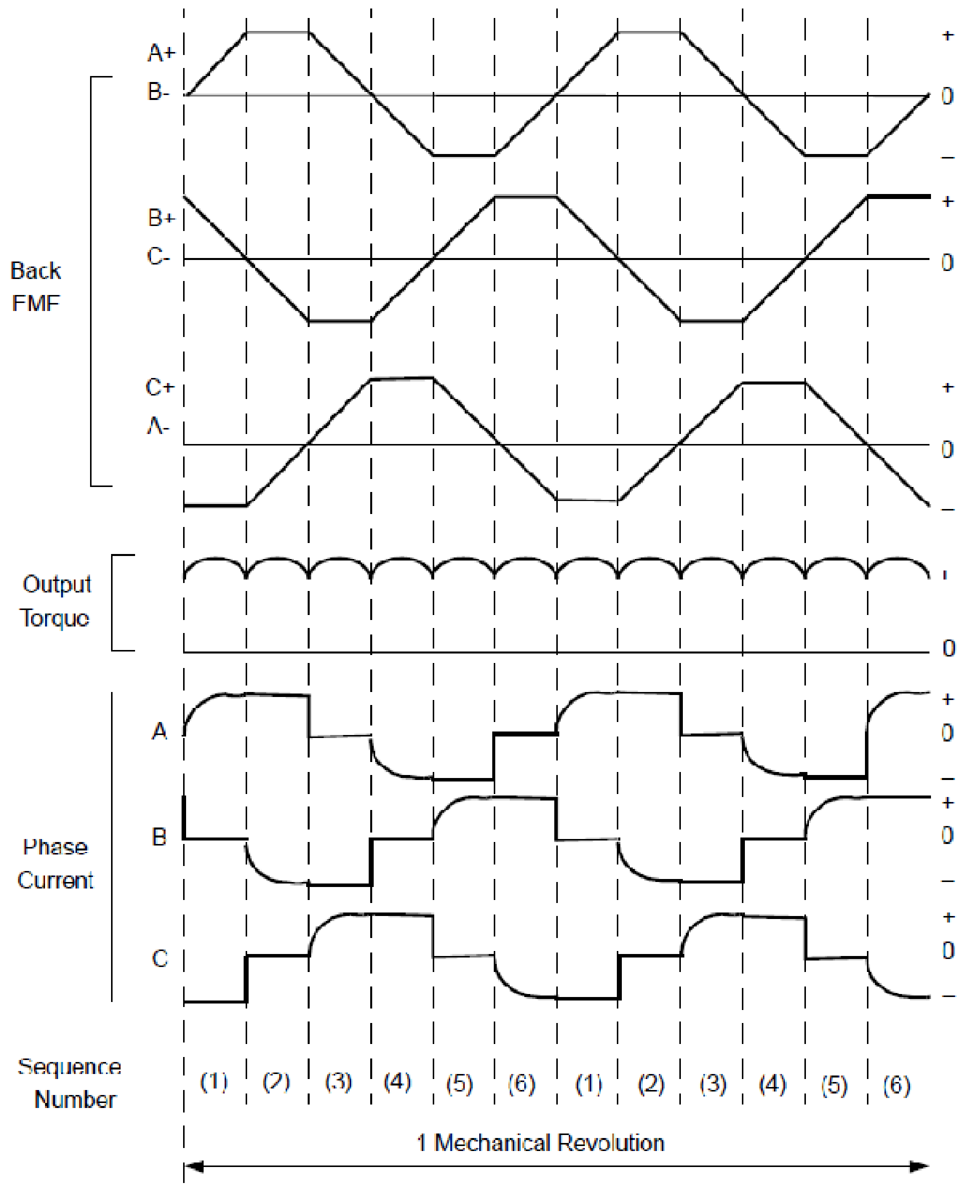


**Figure 19:** Commutation scheme of a BLDC [18].

### 3.3.2 Equivalent circuit

BLDC motors and PMSM have the same equivalent circuit. This circuit is also similar to a brushed DC motor's equivalent circuit. In Figure 20, the equivalent circuit of a PMSM is given for one phase, and in Figure 21, the equivalent circuit of three phases is provided.

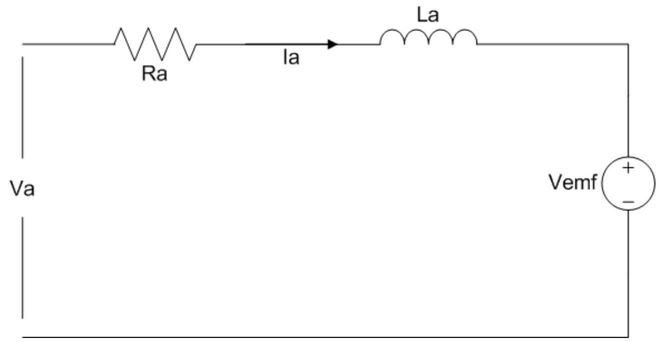


**Figure 20:** Equivalent circuit of a PMSM/BLDC.

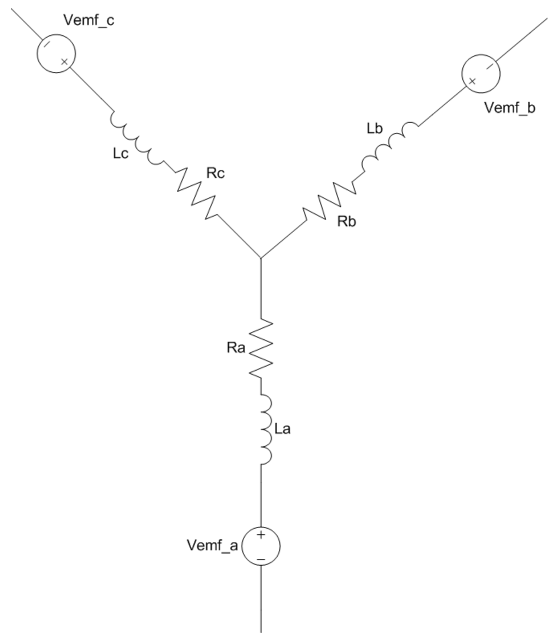


**Figure 21:** Three-phase equivalent circuit of a PMSM/BLDC.

As it can be seen from Figure 20, the motor equivalent circuit is similar to a brushed DC motor's equivalent circuit except the fact that it is a three-phase AC motor. The phases are connected in a wye type connection creating a common wye point. There is a 120 degrees difference between all phases, and the voltages that can be measured from two ends are line-to-line voltages. The wye connected three phase equivalent circuit of a PMSM is shown in Figure 21.

### 3.3.3 Torque-speed characteristics

The torque speed characteristics of a permanent magnet AC motor whether it is a BLDC or PMSM is mostly linear. When talking about the torque speed characteristics of a PMSM or BLDC one can talk about two operational regions. The first region is the intermittent torque zone, where the torque is greater or equal to the rated torque and the speed is equal or less than the rated speed. Unlike universal motors, BLDC and PMSM can operate beyond their rated speeds with a special control scheme called vector control, which will be examined in detail in Chapter 4. The torque speed characteristics of a BLDC/PMSM are shown in Figure 22.

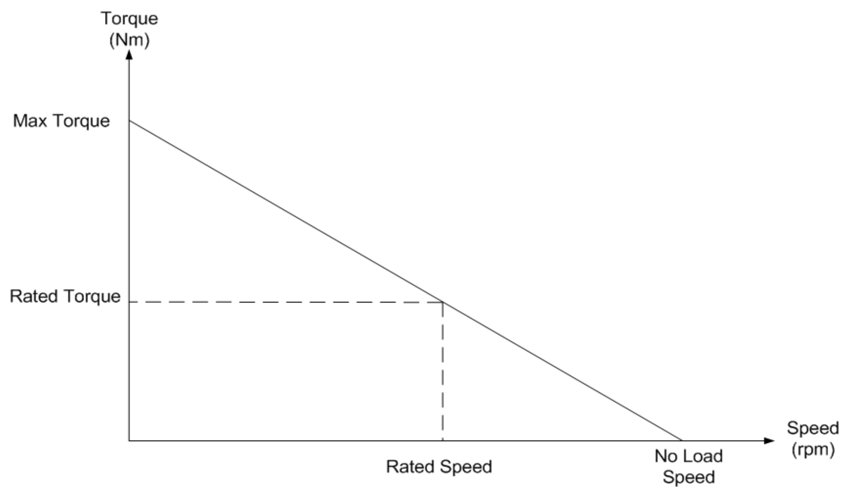


**Figure 22:** Torque speed characteristics of a PMSM/BLDC.

As it can be seen in Figure 22 the torque speed characteristics of a BLDC or PMSM motor is linear. Until the rated speed, the motor can provide relatively high torques, maximum being at start up. After rated speed, motor starts working in field weakening region until no load speed value, at which the torque production ability of the motor is almost zero.

By just looking at the torque speed operation, like universal motors, it would also be appropriate to use a PMSM or BLDC as a washing machine drive component. The key factor here is to choose between the two kinds of similar motors.

### 3.3.4 Advantages and disadvantages of PMSM/BLDC

In this section the advantages of PMSM and BLDC will be evaluated together, no choice will be made, in the next section they will be evaluated separately, and a basis for the choice will be made in the comparison of all motors. General advantageous and disadvantageous properties of a PMSM/BLDC are given below.

#### 3.3.4.1 General advantageous properties of an PM AC motor:

- Highest efficiency
- Little need for maintenance since there are no brushes
- High torque/inertia
- High maximum torque
- Wide speed range and ability to operate in high speeds
- No noises caused by brushes
- Long lifetime

#### 3.3.4.2 General disadvantageous properties of an PM AC motor:

- Need for a special circuit as a supply
- High cost
- Need for a rotor position feedback to effectively control the speed
- Being sensitive to external factors such as temperature rising, mechanical impacts and inverse magnetic field due to the use of permanent magnets

## 3.4 Comparison of Motor Types in Terms of Washing Machine Operation

It is possible to make the comparison of the motors used as drives in washing machines in four different headings: cost, performance, and electronical properties. These headings are of primary importance when choosing a motor for a washing machine and they will be examined in detail separately with keeping the importance level in mind.

### 3.4.1 Cost

It could be said that, in terms of washing operation, the most important criterion when choosing a motor would be the overall cost of the system. The motor that will be equipped by a washing machine is expected to provide the required torque, speed range, have an acceptable comfort level, be feasible in terms of mechanical and structural properties and still be cost effective, in other words, cheap.

Manufacturers always appreciate better performance systems with almost no increase in cost and even some reductions. When building a customer oriented product, without any evasion, the system should be cost effective. This is required for both customer point of view and of course manufacturer point of view, who will have the profit off the cost. The most important item in motor cost is the active materials used in motors. These items can be listed as below

- Conductor volume and type such as copper, aluminum etc.
- Lamination volume, material type
- Cage volume, material type
- Permanent magnet, material and type

If one wants to build an IM, UM, BLDC and PMSM with same power ratings, the conductor volumes, would vary. IM being a motor, which has two windings, which are placed both in stator and rotor, and being one of the lowest efficient motor types, will most probably have the biggest conductor volume. In addition, it is not advised to use aluminum windings instead of copper, since the heating probability of an IM is much higher than any other kind of motor.

Lamination volume highly depends on the conductor used in the motor meaning the volume of windings and other design characteristics. Different motor types have different torque/volume characteristics, which is dependent on the efficiency of the motor. For example, an IM controlled with scalar control method will need to increase in volume to meet the torque/volume ratio of PMSM. Laminations can be made from different materials and with different shapes, optimizations are possible but these methods and calculations have a field of their own and will not be included in the scope of this thesis.

Cage volume is another item that determines the active material cost of motors. Cages are usually made of aluminum for squirrel cage type IM. If the motor is not an IM, there will be no cage cost.

The last item that affects the cost of motors among active materials is the permanent magnets. Permanent magnets are one of the biggest items that affect the cost of PMSM and BLDC motors. Even though different type magnets can be used such as ferrite or NdFeB, they still encompass the one of the biggest ratios in the cost calculation of BLDC motors and PMSM.

It can be said that among the same power rating motors scalar controlled IM will be the most expensive one. That is because, the low efficiency of the IM will make it impossible to reach the power rating of other motors without any increase in size, which means to increase conductor, lamination and cage costs. Also, a scalar controlled IM cannot reach the maximum speed that is required by the washing machine operation without making the motor bigger than it should be, which also reflects to the cost.

For controlled CIM, which is controlled with vector control method, the efficiency will get better and it will be possible to reduce the size of the motor to get the same power rating of other motors.

UM, being one of the motor types with lesser efficiency, makes the size of the UM bigger than others. Also, there are no permanent magnets used and the rotating fields will be created by windings that is why the conductor cost will be high. Because of the inefficiency level, the lamination cost, which is dependent on the motor size, will be high too.

The BLDC and PMSM are similar in structure; this means they will also be similar in terms of cost for same power ratings. The use of permanent magnets is the reason of the high cost of these motors. However, because the power ratings are high for smaller size motors, the lamination and conductor costs are less.

It can be seen that, for same power rating motors, the most expensive motor will be the IM. Following IM will come UM and lastly CIM, BLDC and PMSM will be following these motors. This comparison is done with a grading system, which is based on efficiency and power ratings.

### 3.4.2 Performance

Performance of the motor is another critical issue when choosing a motor. Different types of motor have different performance capacities. Moreover, performance of motor can be examined in different headings such as efficiency, energy consumption, losses, torque/volume ratio, torque capacity, and acoustic noise level.

Efficiency of a motor is an important feature that should be taken in to consideration in many applications. With the popular trend of energy efficient appliances, efficiency of the motors equipped in white goods is even more critical these days. Efficiency of a motor cannot be examined without the energy consumption and losses. Energy consumption of a motor is the energy taken from the source; an efficient motor would use most of this energy to produce torque. However, this is usually not the case and all motors have some losses. Two examples of such losses is copper losses and eddy currents in windings. In addition, the viscous friction of the bearings would also affect the efficiency and energy consumption of the motor, which can be optimized with better designs.

Torque-volume ratio is another important item of the performance criterions of a motor that will be equipped by a washing machine. A motor that will drive a drum is required to be small but high powered in order to provide the torque values required specially in wash cycle. Overall torque capacity of a motor is different from the torque volume ratio. This is the maximum load a motor can handle and is important for washing operation. The last items in performance criteria are the noise level of the motor. A washing machine motor is expected to operate silently in order to provide comfort for the end-user. Commutation noises, acoustic noises caused by brush-commutator structures would give discomfort to the user, and that is why they are avoided.

It can be stated that, scalar controlled IM has the worst performance and is not suitable for a washing operation in terms of performance. The motor with the second worst performance can be pointed as the UM. Because of the amount of windings the UM have higher copper losses. Also it is widely known that UM is not the best motor in terms of efficiency and acoustic noise level. However, this does not change the fact that UM has a significant torque capacity and torque-volume ratio.

BLDC and PMSM are, as previously seen, close to each other in terms of performance. The performance loss occurring in case of BLDC is mostly because of the traditional BLDC control method, trapezoidal control. Because the line voltage is in naturally sinusoidal shape, when trapezoidal voltages are drawn from the line, the efficiency falls. Also the trapezoidal driving scheme causes commutation noises caused by the harmonics.

### 3.4.3 Electrical properties

Electrical properties of motors are mostly the control electronics. The motor is an integral part of the actuator system of a washing machine, but by itself, it becomes useless. The structure needed to run a motor is the motor control electronics and this item is one of the most important item to consider while choosing a motor.

In terms of motor control electronics, there is no need to consider the scalar controlled IM because, it is already seen that scalar controlled IM does not satisfy the required cost and performance criterions.

CIM motor control electronics, BLDC motor control electronics and PMSM motor control electronics are almost the same. These motor control electronics are supposed to control the speed of the motor by changing the multitude and frequency of the input voltage of the motor. In order to do this, a DC Bus structure with a rectifier, a control structure encompassing the microprocessor unit that will have the outputs of PWM signals and the inverter structure that will be driven by these PWM signals and drive the motor itself for the variable speed control. BLDC motor control electronics is slightly less complicated than other two, resulting with less electronical cost. CIM and PMSM can make use of the same type of control method namely; vector control thus, will use almost the same electronics in order to control the motor speed, which is a costly electronics with a more powerful microprocessor.

On the other hand, UM does not need complicated control electronics. Because of the fact that it can be driven by AC line voltage, a simple AC chopper structure such as, a TRIAC can be used for variable speed control.

It could be said that, BLDC seems like the most advantageous of all these motors considering the cost, performance and electronics criteria mentioned. However, PMSM are slightly more efficient and are more silent. For the customer comfort, it can be said that, for washing machine applications, PMSM could be best choice for mid and high segments.

# 4. PMSM DETAILS

The demand in the market and environmental factors constantly have the engineers equip more sophisticated control methods in order to design energy efficient home appliances such as air conditioners and washing machines [3]. Current trend in the world is switching from high power automated industry and appliances to green energy and sustainable energy resources. When it is about sustainable energy resources, two main examples come in to mind being solar and wind. It is a well-known fact that the output power of a photovoltaic panel system or a wind generator is limited. Thus, along with easing the budget of the customers, energy efficient and more sophisticated appliances are inevitably being designed in order to meet the low input power rating that could be provided with sustainable energy sources. In the light of these environmental constrictions and pressure on designers, the newest trend in washing machine design process is to change the older type drive systems for their counterparts, which are more efficient [4].

An example for this traditional drive system is the two speeds IM that can only be found in the cheapest models now and is almost deserted. The second example for a traditional drive system, which is used in majority of the products, is UM which use a simple TRIAC for speed control. It could be said that the modern washing machines will be designed with brushless three phase motors instead of these traditional drive systems [4].

## 4.1 Why PMSM?

Modern high-end washing machines are meant to be eco friendly high tech appliances that can clean clothes with less water, less power and quieter. They should provide high torque at wash cycle, very high speed for spin cycle, and be durable [5].

In Chapter 2, a brief comparison on IM, CIM, UM, BLDC and PMSM is made. It can be seen that best candidates for a drive system of a belt driven washing machine would be CIM, BLDC and PMSM. All three motors are three phase and brushless as mentioned before. So, why should a designer choose PMSM instead of CIM or BLDC motor? This will be evaluated in the following section.

### 4.1.1 PMSM vs. CIM

The answer to the comparison of PMSM and CIM lies in the details of the comparison made and the operational principles of the three types of motors. Firstly, a CIM, having almost the same type of control algorithm as a PMSM, which lets the motor to operate on a wide speed region with a good dynamical response, is less energy efficient than a PMSM. That is mostly because, induction machines, because of their characteristics, contains conductor materials such as copper on stator windings and aluminum on the cage of the rotor. Although PMSM also have conductors in stator windings, it is not equipped with extra conductors on the rotor since permanent magnets are used to provide the rotor field. This fact clearly explains the efficiency difference between two types of motors. A CIM would have higher copper losses than a PMSM resulting with power loss and increased heating on the rotor. High copper losses are not wanted, that is for sure. However, the heating tendency of the motor, which also depends on the copper losses, is also important. In washing machine operation where the motor is meant to operate in low speed region with a high load in wash cycle, the motor temperature will rise due to the high phase currents caused by high load torque. Since the parameters of the motor such as resistance and inductance are dependent on the operating temperature. The dynamic behavior of the motor will change with the rising temperature. That is why, in terms of heating and losses, PMSM is better than a CIM.

### 4.1.2 PMSM vs. BLDC

The second competitor of PMSM is BLDC, which is a widely used motor type not only in industry, but also in washing machines. There are two main problems with using a BLDC motor, which is caused by the winding type, and driving scheme.

As mentioned before BLDC is driven with a six step switching sequence which is also called trapezoidal control. This control scheme, contains harmonics due to its characteristics. These harmonics cause both electrical and audible noise, which is also called commutation noises. Electrical types of noises can be filtered with low pass type filters, but the audible noises are not desired when the customer satisfaction and comfort is of concern which is typical to appliances. Since PMSM is driven with sinusoidal type switching scheme, the current harmonics are lower. This means that the audible and electrical noise caused by harmonics is lower in PMSM. Also, the motor core losses and the current peak value are lower in PMSM [6].

Along with these problems, trapezoidal control causes fluctuations on the torque output. These fluctuations are not desired since the washing machine load is dynamically challenging. Additionally, the trapezoidal control is not satisfactory in terms of dynamical response. The load of the washing machine greatly varies with the amount of the laundry, within wash cycle because of the dynamical behavior of the tumbling operation, and with different cycle selections e.g. wash cycle and rinsing cycle. This behavior demands a good dynamical response from the control scheme and this can be provided only with sophisticated control algorithms such as vector control [3].

As a summary, permanent magnet synchronous motors, in other words permanent magnet sinusoidal drives are the most suitable motors for washing machines. The advantages and main reasons for choosing a PMSM can be listed as below [7].

Due to the use of permanent magnets,

  - Brushes are eliminated
  - Slip rings are eliminated

- Higher efficiency due to lower copper losses in rotor
- Easier cooling operation through stator since copper and iron losses are concentrated there
- Higher torque-volume ratio
- Lower electrical and acoustic noises
- Design flexibility due to the used magnet type and arrangement
- Suitable for the use of advanced control algorithms such as vector control which brings better dynamical response

### 4.2 Mathematical Model of PMSM

Vector control algorithm that will be used for speed control of the motor is an algorithm, which is dependent on the motor model. That is why, derivation of the electrical and mechanical model of the PMSM is crucial. While deriving the model of the motor it is assumed that

1. Stator windings are balanced with sinusoidally distributed mmf (magnetomotive force).
2. The inductance versus rotor position is sinusoidal.
3. The saturation and parameter changes are neglected. [8]

When the mathematical model of a PMSM is of concern it should be noted that three different models can be written. The first model of the PMSM would be the three phase variable model, which consists of three phase alternating current and voltage values that varies with the position of the rotor. The second model can be defined as the α-β model of the PMSM. Lastly, the third model of concern is the d-q model.

### 4.2.1 Phase variable electrical model

The phase variable model of a PMSM can be derived from the three-phase voltage equation given in (4.1).

$$\vec{V_s} = R_s\vec{I_s} + \frac{d\vec{\lambda}_s}{dt} \quad \textbf{(4.1)}$$

Where, $\vec{V_s}$ defines the stator windings' voltage vector, $\vec{I_s}$ current vector, $\vec{\lambda}_s$ flux linkage vector and lastly $R_s$ is the stator winding's resistance. The equation can be decoupled to each phase as given below:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} R_sI_a(t) + \frac{d\lambda_a(t)}{dt} \\ R_sI_b(t) + \frac{d\lambda_b(t)}{dt} \\ R_sI_c(t) + \frac{d\lambda_c(t)}{dt} \end{bmatrix} \quad \textbf{(4.2)}$$

As can be seen from (4.3), the voltage value for each phase denoted by $V_a$, $V_b$, and $V_c$ respectively varies depending on the frequency meaning the phase of the rotor. $I_a$, $I_b$, $I_c$ represent the currents of each phase and $\lambda_a$, $\lambda_b$, $\lambda_c$ represents the flux linkages of each phase. The currents for each phase can be written similarly and is given in (4.3).

$$\begin{bmatrix} I_a(t) \\ I_b(t) \\ I_c(t) \end{bmatrix} = |\vec{I_s}| \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad \textbf{(4.3)}$$

Where, $|\vec{I_s}|$ is the stator current's magnitude and $\omega$ is the frequency of the stator's field. In order to finalize the phase variable model of the PMSM, the flux linkages should also be denoted. The flux vector $\vec{\lambda}_s$ can also be decoupled similarly. The flux linkages of each phase can be written in the matrix form as in (4.4).

$$\begin{bmatrix} \lambda_a(t) \\ \lambda_b(t) \\ \lambda_c(t) \end{bmatrix} = \begin{bmatrix} L_s I_a(t) \\ L_s I_b(t) \\ L_s I_c(t) \end{bmatrix} + \begin{bmatrix} \Lambda_m \sin(\omega t) \\ \Lambda_m \sin(\omega t - \frac{2\pi}{3}) \\ \Lambda_m \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \tag{4.4}$$

Where $\omega t$ can be defined as $\theta(t)$ and $\Lambda_m$ is the constant flux vector of the permanent magnets, which is also named as the motor coefficient. When (4.1) is examined it is apparent that the derivative of the flux linkages for each phase is needed in order to develop the model. Supposing the rotor is rotating at a constant speed, the derivatives of the flux linkages with respect to time can be obtained as in (4.5).

$$\begin{bmatrix} \frac{d\lambda_a(t)}{dt} \\ \frac{d\lambda_b(t)}{dt} \\ \frac{d\lambda_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} L_s \frac{dI_a(t)}{dt} + \omega\Lambda_m \cos(\theta) \\ L_s \frac{dI_b(t)}{dt} + \omega\Lambda_m \cos(\theta - \frac{2\pi}{3}) \\ L_s \frac{dI_c(t)}{dt} + \omega\Lambda_m \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{4.5}$$

After we have the derivative of the flux linkages for each phase with respect to time, we can write a voltage equation that will finalize the derivation of the electrical model of the PMSM in a matrix form. The model is given in (4.6).

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} R_s I_a(t) + L_s \frac{dI_a(t)}{dt} + \omega\Lambda_m \cos(\theta) \\ R_s I_b(t) + L_s \frac{dI_b(t)}{dt} + \omega\Lambda_m \cos(\theta - \frac{2\pi}{3}) \\ R_s I_c(t) + L_s \frac{dI_c(t)}{dt} + \omega\Lambda_m \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{4.6}$$

As can be seen, the differential equations describing the voltages and currents of each phase are nonlinear. In order to utilize the benefits of linear control structures, in terms of stability and controller design it is essential to linearize the equations [8]. This linearization can be made with a series of transformations and rotations. These transformations can be seen as a matter of perspective. As stated in [9] "The key principle transformations is that either rotating windings carrying DC currents or fixed windings carrying AC currents can produce a rotating field system. Another principle is that the field produced by any combination of multiphase windings can be produced by using two quadrature windings”

With these two principles in mind, two other kinds of models for a PMSM can be derived, namely, α-β model and d-q model.

### 4.2.2 Mathematical model of PMSM in α-β reference frame

In order to transform the phase variable electrical model of the PMSM in to the mathematical model in α-β reference frame, certain transformation named Clarke Transform should be applied.

Clarke transformation is used to transform the three phase AC current and voltage values given in $(a, b, c)$ reference frame as also named phase variable electrical model to two phase AC current and voltage values given in $(\alpha\beta 0)$ reference frame. The transformation coordinates are given in Figure 23.

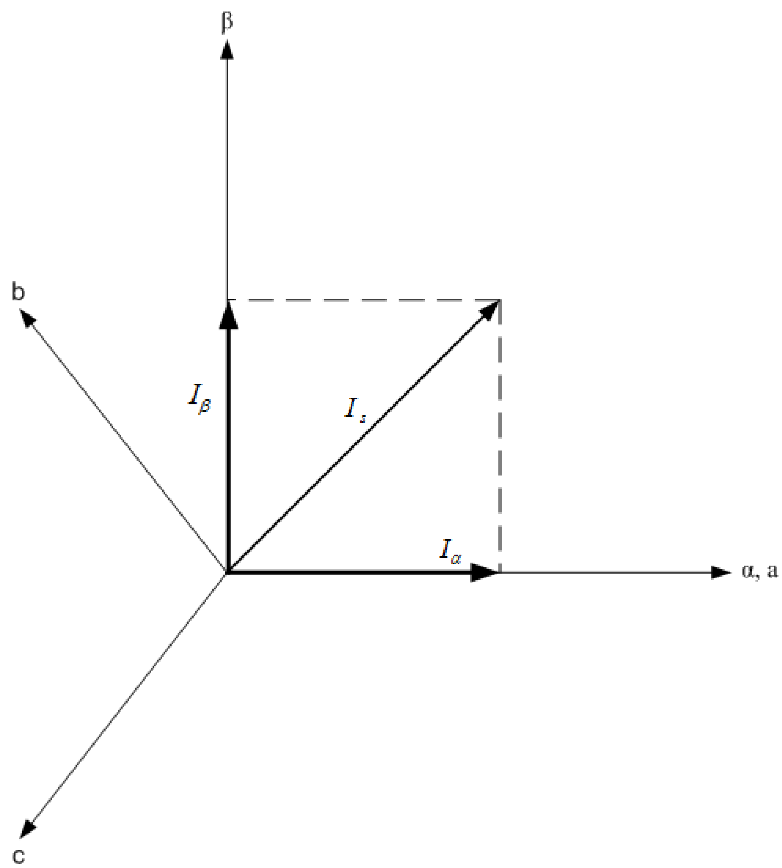


**Figure 23:** Relationship between $(\mathbf{a}, \mathbf{b}, \mathbf{c})$ and $(\boldsymbol{\alpha\beta 0})$ reference frames.

As can be seen from the figure, in this transformation, the magnitude of the stator current phasor does not change. The transformation moves a three axis, two-dimensional coordinate system onto a two-axis system keeping the same reference being stator. The transformation is given in (4.7) and the block diagram can be shown as Figure 24.

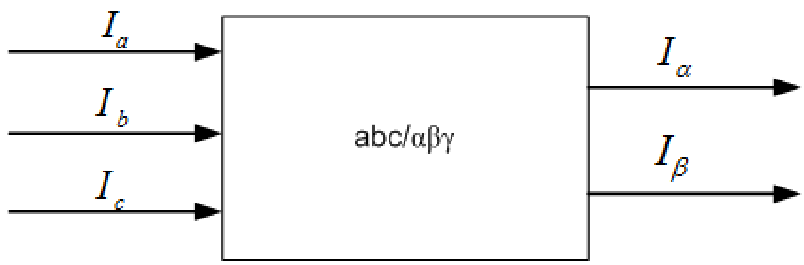


**Figure 24:** Block diagram of clarke transform.

$$T_{abc,\alpha\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \quad \textbf{(4.7)}$$

The values for the $\gamma$ frame do not have any meanings and not used in model derivation. Also, the reverse transformation matrix $T_{abc,\alpha\beta}^{-1}$ can be given as shown in (4.8).

$$T_{\alpha\beta 0,abc}^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix} \quad \textbf{(4.8)}$$

The inverse Clarke transform is needed when it is desired to change the reference system from a two-phase reference frame to a three-phase reference frame i.e. calculating real phase currents in order to apply PWM.

With the transformation matrix given the mathematical model of PMSM in ($\alpha\beta 0$) reference frame can be derived with the following equation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = T_{abc,\alpha\beta\gamma} \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} \tag{4.9}$$

Voltage equations of $\alpha$ and $\beta$ axes can be written in a compact matrix form based on (4.9) as shown in (4.10).

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} R_s I_a(t) + \frac{d\lambda_a(t)}{dt} \\ R_s I_b(t) + \frac{d\lambda_b(t)}{dt} \\ R_s I_c(t) + \frac{d\lambda_c(t)}{dt} \end{bmatrix} \tag{4.10}$$

Carrying out the multiplication will result with the equations (4.11) and (4.12) Writing this equation in a more compact form and excluding the 0 axis would give us (4.13).

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \left[R_s I_a(t) + \frac{d\lambda_a(t)}{dt}\right] - \frac{1}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] - \frac{1}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \\ \frac{\sqrt{3}}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] - \frac{\sqrt{3}}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \\ \frac{\sqrt{2}}{2}\left[(R_s I_a(t) + \frac{d\lambda_a(t)}{dt}\right] + \frac{\sqrt{2}}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] + \frac{\sqrt{2}}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \end{bmatrix} \tag{4.11}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \left[R_s I_a(t) + \frac{d\lambda_a(t)}{dt}\right] - \frac{1}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] - \frac{1}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \\ \frac{\sqrt{3}}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] - \frac{\sqrt{3}}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \\ \frac{\sqrt{2}}{2}\left[(R_s I_a(t) + \frac{d\lambda_a(t)}{dt}\right] + \frac{\sqrt{2}}{2}\left[R_s I_b(t) + \frac{d\lambda_b(t)}{dt}\right] + \frac{\sqrt{2}}{2}\left[R_s I_c(t) + \frac{d\lambda_c(t)}{dt}\right] \end{bmatrix} \tag{4.12}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R_s I_a(t) + \frac{d\lambda_a(t)}{dt} \\ \frac{1}{\sqrt{3}}\{R_s[I_b(t) - I_c(t)] + \frac{d\lambda_b(t)}{dt} - \frac{d\lambda_c(t)}{dt}\} \end{bmatrix} \qquad \textbf{(4.13)}$$

If this transformation is applied to current and flux linkage equations too, the (4.14) and (4.15) will be derived for each respectively. Then we can write the compact model of the PMSM in α-β reference frame.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} I_a \\ \frac{1}{\sqrt{3}}(I_b - I_c) \end{bmatrix} \qquad \textbf{(4.14)}$$

$$\begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix} = \begin{bmatrix} \lambda_a \\ \frac{1}{\sqrt{3}}(\lambda_b - \lambda_c) \end{bmatrix} \qquad \textbf{(4.15)}$$

Substituting the $I_a$, $I_b$, $I_c$, $\lambda_a$, $\lambda_b$, and $\lambda_c$ with corresponding $I_\alpha$, $I_\beta$, $\lambda_\alpha$, and $\lambda_\beta$ quantities given in (4.13) we get the equation shown in (4.16).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R_s I_\alpha + \frac{d\lambda_\alpha(t)}{dt} \\ \frac{1}{\sqrt{3}}\{R_s \sqrt{3} I_\beta + \sqrt{3}\frac{d\lambda_\beta(t)}{dt}\} \end{bmatrix} \qquad \textbf{(4.16)}$$

Carrying out the simplifications, we will eventually get the voltage equations model denoted in α-β reference frame.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R_s I_\alpha + \frac{d\lambda_\alpha(t)}{dt} \\ R_s I_\beta + \frac{d\lambda_\beta(t)}{dt} \end{bmatrix} \qquad \textbf{(4.17)}$$

As can be seen from the model shown in (4.17), it is apparent that the model is similar to the one in a-b-c reference frame, namely phase variable model. Thus, the flux linkage equations can be given as in (4.18) and derived with respect to time giving the final identity of flux linkages shown in (4.19).

$$\begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix} = \begin{bmatrix} L I_\alpha + \Lambda_m \cos(\theta) \\ L I_\beta + \Lambda_m \sin(\theta) \end{bmatrix} \qquad \textbf{(4.18)}$$

$$\begin{bmatrix} \frac{d\lambda_\alpha(t)}{dt} \\ \frac{d\lambda_\beta(t)}{dt} \end{bmatrix} = \begin{bmatrix} L\frac{dI_\alpha}{dt} - \omega\Lambda_m \sin(\theta) \\ L\frac{dI_\beta}{dt} + \omega\Lambda_m \cos(\theta) \end{bmatrix} \quad \textbf{(4.19)}$$

Finally, the mathematical model of the PMSM denoted in α-β reference frame can be obtained as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R_s I_\alpha + L\frac{dI_\alpha}{dt} - \omega\Lambda_m \sin(\theta) \\ R_s I_\beta + L\frac{dI_\beta}{dt} + \omega\Lambda_m \cos(\theta) \end{bmatrix} \quad \textbf{(4.20)}$$

### 4.2.3 Mathematical model of PMSM in d-q reference frame

In order to obtain the mathematical model of PMSM in d-q reference frame, which is also called as the dynamical model of the PMSM, another transformation should be applied following the Clarke transformation. The second transformation, which is called Inverse Park transformation, is a rotation matrix. The idea behind the transformation is the perspective from the rotating current phasor. If the coordinate system and reference frame is rotated with the same frequency as the current itself, the AC current in the stationary reference frame will act like a DC current in the rotating reference frame. The rotating reference frame is called $(dq0)$ reference frame. The transformation coordinates with respect to $(\alpha\beta0)$ reference frame is shown in Figure 25 and the rotation matrix is given in (4.21). Also, the block diagram of the transformation is given in Figure 26.

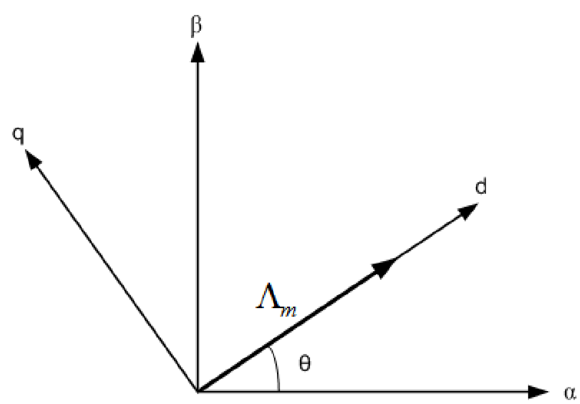


**Figure 25:** Relationship between d-q and α-β reference frames.

$$R_{dq,\theta} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \quad \textbf{(4.21)}$$

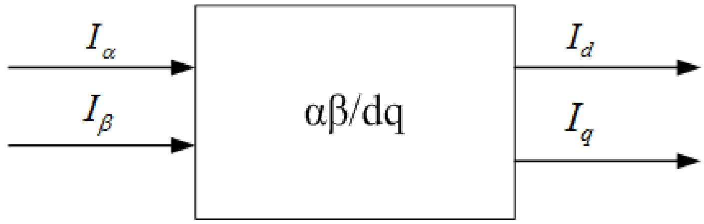


**Figure 26:** The block diagram of park transformation.

As can be seen from the figure, the d axis is chosen in the direction of the magnetic vector $\Lambda_m$ stating rotor's magnetic field and the whole d-q coordinate system is rotated around the origin with the position angle θ [10]. The voltage equations can be derived by applying the rotation given in (4.22).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R_{dq,\theta} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad \textbf{(4.22)}$$

If the multiplication with the rotation matrix is written and the multiplications are carried out the followings steps will be taken. Firstly, the currents in d-q reference frame will be obtained by using rotation matrix on current identities in α-β reference frame. The result is shown in (4.24).

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad \textbf{(4.23)}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} I_\alpha \cos(\theta) + I_\beta \sin(\theta) \\ -I_\alpha \sin(\theta) + I_\beta \cos(\theta) \end{bmatrix} \quad \textbf{(4.24)}$$

Also the derivatives of d-q axis currents with respect to time in terms of currents in α-β reference frame can be given as in (4.25).

$$\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \frac{dI_\alpha}{dt}\cos(\theta) + \frac{dI_\beta}{dt}\sin(\theta) + \omega\left(I_\alpha \cos(\theta) + I_\beta \sin(\theta)\right) \\ -\frac{dI_\alpha}{dt}\sin(\theta) + \frac{dI_\beta}{dt}\cos(\theta) - \omega\left(-I_\alpha \sin(\theta) + I_\beta \cos(\theta)\right) \end{bmatrix} \quad \textbf{(4.25)}$$

Finally, substituting the multipliers of ω in (4.25) with identities given in (4.24), we get the following.

$$\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \frac{dI_\alpha}{dt}\cos(\theta) + \frac{dI_\beta}{dt}\sin(\theta) + \omega I_q \\ -\frac{dI_\alpha}{dt}\sin(\theta) + \frac{dI_\beta}{dt}\cos(\theta) - \omega I_d \end{bmatrix} \tag{4.26}$$

After the currents are found, the rotation for the voltage equations can be evaluated. Writing the identities given in (4.21) in (4.22) we get (4.27).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V_\alpha \cos(\theta) + V_\beta \sin(\theta) \\ -V_\alpha \sin(\theta) + V_\beta \cos(\theta) \end{bmatrix} \tag{4.27}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} R_s I_\alpha + L\frac{dI_\alpha}{dt} - \omega\Lambda_m \sin(\theta) \\ R_s I_\beta + L\frac{dI_\beta}{dt} + \omega\Lambda_m \cos(\theta) \end{bmatrix} \tag{4.28}$$

From here on, the current values and derivatives of these currents with respect to time in d-q reference frame given in (4.24) and (4.26) will be used to arrange the equations accordingly. When (4.28) is written in open form, we get two equations for d-q axis voltage values given in (4.29) and (4.30).

$$\begin{aligned} V_d = {} & R_s(I_\alpha \cos(\theta) + I_\beta \sin(\theta)) + L\left(\frac{dI_\alpha}{dt}\cos(\theta) + \frac{dI_\beta}{dt}\sin(\theta)\right) \\ & - \omega\Lambda_m \sin(\theta)\cos(\theta) + \omega\Lambda_m \cos(\theta)\sin(\theta) \end{aligned} \tag{4.29}$$

$$\begin{aligned} V_q = {} & R_s(-I_\alpha \sin(\theta) + I_\beta \cos(\theta)) + L\left(-\frac{dI_\alpha}{dt}\sin(\theta) + \frac{dI_\beta}{dt}\cos(\theta)\right) \\ & + \omega\Lambda_m \sin^2(\theta) + \omega\Lambda_m \cos^2(\theta) \end{aligned} \tag{4.30}$$

Arranging equations (4.29) and (4.30) with applying necessary trigonometric simplifications the equations yield:

$$V_d = R_s(I_\alpha \cos(\theta) + I_\beta \sin(\theta)) + L\left(\frac{dI_\alpha}{dt}\cos(\theta) + \frac{dI_\beta}{dt}\sin(\theta)\right) \tag{4.31}$$

$$V_q = R_s(-I_\alpha \sin(\theta) + I_\beta \cos(\theta)) + L\left(-\frac{dI_\alpha}{dt}\sin(\theta) + \frac{dI_\beta}{dt}\cos(\theta)\right) + \omega\Lambda_m \quad \textbf{(4.32)}$$

Now, we can use the identities given in (4.24) and (4.26) for substituting the multiplier term of the resistance and inductance values. When the substitution is done, finally, the voltage equations in d-q reference frame, being the mathematical model in d-q reference frame will be derived. The equations for $V_d$ and $V_q$ are given in (4.33) and (4.34) respectively.

$$V_d = R_s I_d + L\frac{dI_d}{dt} - \omega L I_q \quad \textbf{(4.33)}$$

$$V_q = R_s I_q + L\frac{dI_q}{dt} + \omega L I_d + \omega\Lambda_m \quad \textbf{(4.34)}$$

Where,

$R_s$: Stator resistance value

$L$ : Stator inductance value

$\omega$: Rotor frequency in stator reference frame ($\omega = p\omega_r,\ p: pole\ pairs$)

$\Lambda_m$: Rotor magnetization constant

$V_d$: Voltage in d-axis

$V_q$: Voltage in q-axis

$I_d$: Current in d-axis

$I_q$: Current in q-axis

It should be noted that all voltage and current values are DC values after these transformations. As a summary, this method is used to simplify the highly nonlinear mathematical expressions of a PMSM and degrade them into the form of a simple DC motor in order to use all the benefactions of the linear control theory. The idea behind the transformations can be summarized as being a matter of perspective. Since a magnetic field can be created by AC currents on three phase windings. If one can imagine self being at the stator and looking at the magnetic field created by it, he should see two dimensional, AC waveforms. If a field produced by multiphase windings can also be produced by two quadrature windings, it is possible to degrade the system into a two-phase system namely, α-β axis with the use of Clarke Transform from mathematical point of view. Then, if one can imagine self-watching the field from stator, he should see a rotating field carrying AC quantities. If then one can watch this same field, from rotor's perspective which rotates with the same frequency as the field, he should see a stationary field carrying DC quantities. The whole idea behind transforming the mathematical identities is this simple variance in perspective.

Moreover, the dynamical model of the PMSM cannot be completed without including the torque equation. The torque equation consists of two parts: the torque produced by the motor and the torque used by the load. As seen in (4.35), the left hand side of the equation is the torque produced by the flux, and the right hand side of the equation is the torque used by the motor for driving the load, self-inertia and viscous friction. The mechanical model of the PMSM is given in (4.35).

$$\frac{3}{2} p I_q \Lambda_m = B\omega_r + J\frac{d\omega_r}{dt} + T_L \qquad \textbf{(4.35)}$$

Where,

$p$ : Pole pairs

$\omega_r$: Rotor speed in rad/s ($\omega = p\omega_r,\ p{:}\,pole\ pairs$)

$\Lambda_m$: Magnetization constant

$B$ : Viscous friction constant

$J$ : Motor inertia

$T_L$: Load torque

$I_q$: q-axis current

# 5. APPLICATION of SENSORLESS VECTOR CONTROL ALGORITHM on WASHING MACHINES

The aim of the appliance producers is to increase the efficiency of their products while reducing the audible noise, of course with minimum addition to the system cost. The driving force behind these objectives is both the government regulations on energy consumption and customers' tendency for buying green appliances. The main reason behind using sophisticated motor control algorithms, which enhance the efficiency for appliances equipped with motors, is the regulations on energy consumptions and the demand in market for green appliances [19].

## 5.1 Why Vector Control?

Washing machines equipped with PMSM can make use of a well-known and settled control technique known as vector control or field oriented control (FOC). The application of vector control in mass production was still not possible until a couple of years ago. However, the developing semiconductor industry made it possible to use powerful microcontroller units or digital signal processors in mass production with the fall in their prices. It is now possible to equip a washing machine with a microprocessor that costs much less than it was five years ago and more powerful than its ancestor by far.

Vector control algorithm is used for three phase AC machines such as PMSM and IM, when constant torque, high efficiency, less torque ripple and good dynamical response is desired for constant speed reference. An example torque speed characteristics of a motor control with vector control scheme is given in Figure 27. As it can be seen, until a critical speed value, which is the nominal speed of the motor, the motor can provide constant torque. After this speed value if it is still desired to increase the speed, the operation region will change to constant power region and different control approaches should be used.

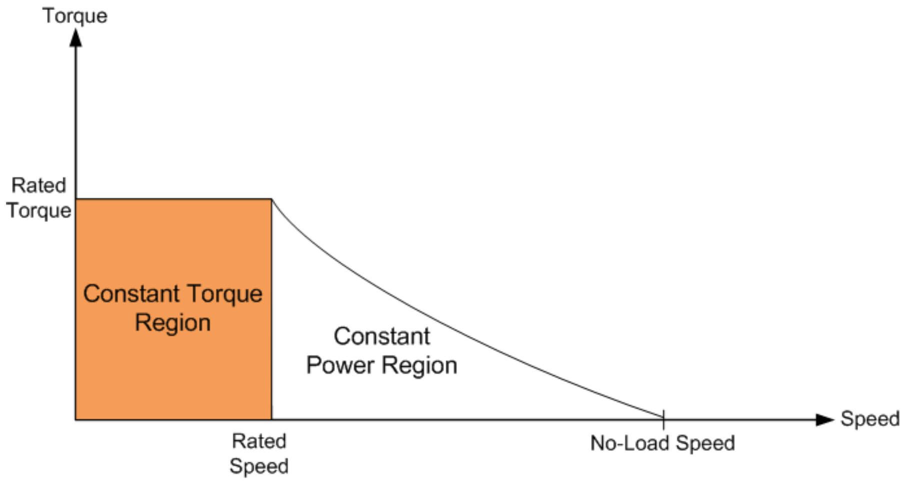


**Figure 27:** Torque speed characteristics of vector control.

Vector control algorithm is constantly gaining popularity in appliance industry. Washing machines, dishwashers, air conditioners, fridge compressors are being equipped with vector controlled alternatives. The reasons for this if it may be called – evolution, can be listed as follow:

- Higher Efficiency [20]
- Improved dynamical response [19]
- Less torque ripple comparing to other techniques [20]
- Better acceleration and deceleration rates [19]
- The most optimal torque production which needs the least current [19]
- Ensuring limited phase currents [19]
- Greatest cost benefit which can be improved with sensorless methods
- Vector controlled PMSM are electrically and acoustically less noisy than their counter parts which enhance customer comfort
- Higher reliability if the vector control algorithm is designed sensorless
- Eases load balancing for washing machines [21]

**5.2 Sensorless Vector Control General Scheme**

When a control algorithm that is designed to control both the voltage and the frequency of the supply voltage of a motor, is used the general scheme of the circuit is of a pretty well known topology. We can examine the motor control circuit in six parts, and the general block figure of the circuit is shown in Figure 28.

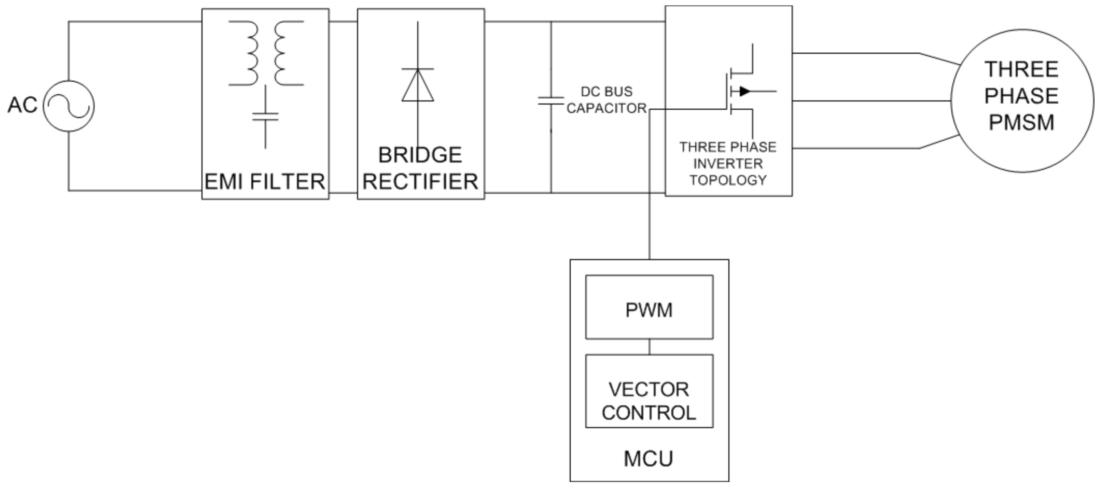


**Figure 28:** General scheme of motor control circuit.

First part is, since our implementation is a washing machine, an EMI suppressor, which is used in the supply layer of the motor control circuit. This suppressor, in other words filter is used because there are regulations, which strictly limit the EMI an appliance can have, and if the appliance cannot meet these standards it cannot be sold in the respective countries. The second part that follows the EMI suppressor is a bridge rectifier, which rectifies the AC supply voltage and makes it possible to use a PWM method in order to perform speed control by changing both magnitude and the frequency of the voltage driving the motor.

The third layer of the circuit is the DC Bus capacitor, which reduces the current ripple after it is rectified. The fourth level of the circuit is the inverter circuit and lastly the fifth level of the circuit is the load, being the motor that is to be driven. It should be noted that, when Figure 28 is examined carefully, there actually is another part shown which is the microprocessor unit. We can say that microprocessor unit is a sub-layer of the inverter circuit, since it generates the PWM signals used to drive the switches. But, it is also not wrong to state that, microprocessor unit is the brain of the speed control operation while the power circuit which consists of the five layers mentioned is the heart.

The PWM signals are generated with respect to the control algorithm operating in the microprocessor unit. The control algorithm used for this application is sensorless vector control and all operations are done using this power circuit model.

Vector control as can also be understood if the name is concerned, is a control method, which is based on the flux vectors in rotor reference frame. The rotor reference frame model, which was examined in detail under the name d-q reference frame model, is used throughout the control scheme. Hence, it is appropriate to also say that vector control is a model dependent control algorithm. The simplified block diagram of the algorithm is shown in Figure 29, which states the general scheme of the vector control method.

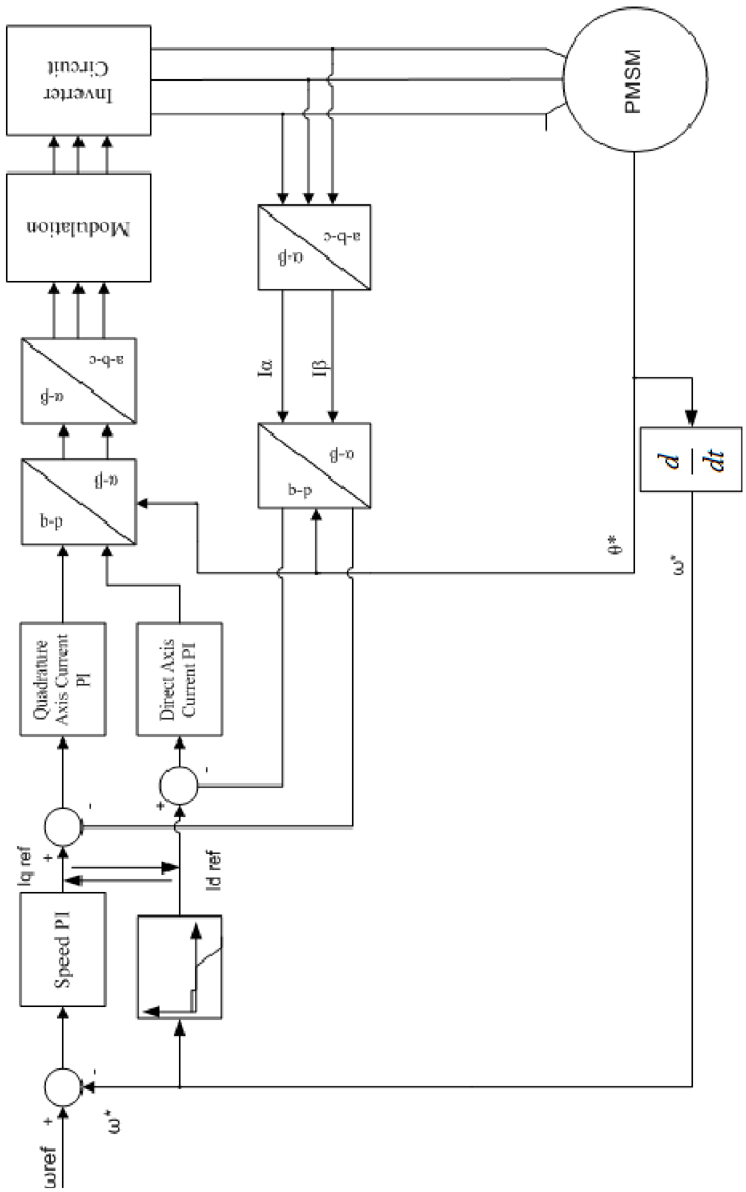


**Figure 29:** General block diagram of vector control.

If Figure 29 is examined, it can be noticed that the first step of the algorithm is to evaluate the speed error in the speed control loop. From this, follows two current errors, which are direct and quadrature currents' errors, are evaluated in current control loops. The outputs of these cascaded control loops are the direct and quadrature axis voltages, which should be firstly transformed in to voltages in α-β reference frame and then voltages in a-b-c three-phase reference frame. Lastly, the PWM unit is driven with the voltage references obtained after the transformations. This PWM signal can be used to drive an inverter structure and finally the speed control of the motor can be carried out.

### 5.3 Sensorless Vector Control Application Details

It was stated that the speed control of PMSM requires the speed and position data of the motor. This position and speed data may be gathered with sensors such as incremental encoders or hall sensors. However, it is also stated that use of position sensors increase the mechanical complexity, cost, decrease the robustness and reliability and increase the maintenance requirements [7]. The most critical disadvantages of using sensors in washing machine operation are that the use of sensors reduce the reliability of the control structure and generally increase the cost [22]. Reliability reduction occurs because of the fact that a single error in the sensors or sensing operation may end up with a failure in the whole system. On the other hand, the cost would increase in encoder type of position sensors because these types of sensors are usually expensive parts used in applications which needs accurate positioning. The hall sensors usually increase the cost not because of the fact that they are expensive, but the installment of hall sensors in the motor requires more effort and makes the design of the motor more complex.

The sensorless vector control scheme however, needs no sensors for the measurement of the rotor position. In addition, especially in washing machine operation the control of the rotor position is not necessary, thus an approximate estimation of the rotor position and speed, which will not affect the dynamics of the operation, is sufficient. Even though the scheme is sensorless, the rotor position and speed still need to be estimated through a series of calculations, which also requires the estimation of the flux linkages. A more detailed block diagram for sensorless vector control is given in Figure 30.

The sensorless control schemes also vary according to the estimation process. The estimation can be done with open loop estimators using measured stator voltage and currents, stator phase third-harmonic voltage based estimators, back EMF based estimators, observer based estimators, saliency based estimators or artificial intelligence based estimators [7]. Typically, in washing machine operation, these estimations are done either using open loop estimators or saliency-based estimators. Since the motor used in the application is a non-salient permanent magnet motor, the approach for estimation process within the scope of this thesis is to use open loop estimators, which calculate flux, position and speed using the phase current measurements.

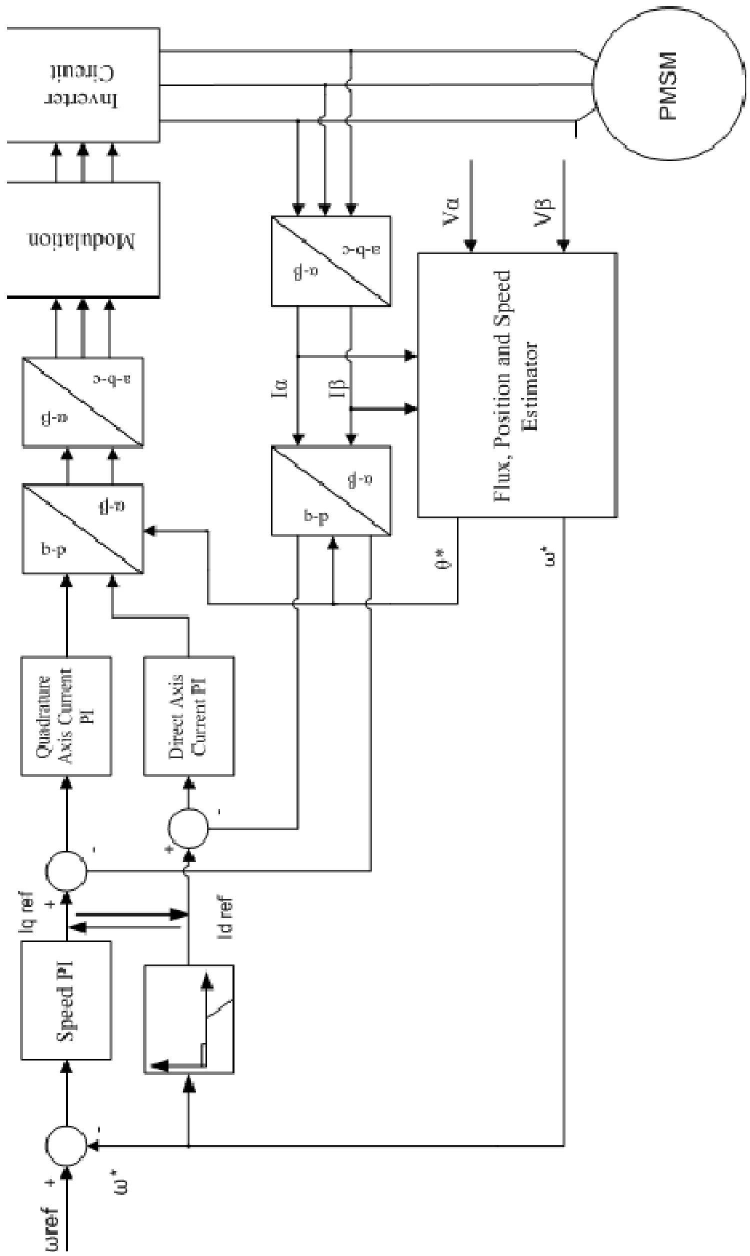


**Figure 30:** Detailed block diagram of sensorless vector control.

### 5.3.1 Open loop flux estimation

In the washing machine prototype, which was used as an experiment platform, the prototype motor used was of a type, which had same inductance values on d and q axes. Therefore, the use of saliency based estimation methods for rotor flux's was not possible since they depend on the difference of the direct and quadrature axis inductances. In addition, intelligent methods such as observer based methods, which make use of extended kalman filters, or neural networks were also out of scope, since in appliances, the MCUs used are of low cost segment and cannot process algorithms with high computational load. The back EMF based methods can also be used, but the choice of estimation method for this particular application was the use of open loop flux estimations, which require the least computational effort.

The open loop flux estimators calculating the flux by making use of current measurements of motor phases. This method is also an indirect back EMF estimation method in open loop. The estimation of the rotor flux needs the computation which requires either one shunt resistor in the DC Bus or two to three shunt resistors in the low side switches of the inverter topology [9].

The estimation method used in the application is to measure the phase currents and reconstruct the flux equation in α-β reference frame. In order to do this, the phase currents are measured through shunt resistors in low side switches of the inverter topology and then the transformation from a,b,c reference frame to α-β reference frame is performed. In (5.1) and (5.2), voltage equations are used to calculate the back EMF, which are obtained with the transformed phase currents.

$$V_\alpha = R_s I_\alpha + \frac{d\lambda_\alpha}{dt} \tag{5.1}$$

$$V_\beta = R_s I_\beta + \frac{d\lambda_\beta}{dt} \tag{5.2}$$

It should be noted that the flux values in α-β reference frame can be obtained by integrating the back EMF calculated. If the integration is performed, the following equations will be obtained which will result with the calculation of the flux values in α-β reference frame. Where, $\lambda_\alpha$ and $\lambda_\beta$ are the flux linkages in stator reference frame,

$\lambda_{\alpha 0}$ and $\lambda_{\beta 0}$ are the initial conditions for the integral and $(V_\alpha - R_s I_\alpha)$, $\left(V_\beta - R_s I_\beta\right)$ are the back EMF values calculated from (5.1) and (5.2) respectively.

$$\lambda_\alpha = \lambda_{\alpha 0} + \int_0^t (V_\alpha - R_s I_\alpha) dt \tag{5.3}$$

$$\lambda_\beta = \lambda_{\beta 0} + \int_0^t \left(V_\beta - R_s I_\beta\right) dt \tag{5.4}$$

This integration can be done with two methods in digital platforms such as a MCU. The first approach would be calculation of the accumulation over time, which means an open loop integrator structure. The second approach, which is more computational effort efficient since it does not require arrays for data storing, is the use of low pass filters as integrators.

A digital low pass filter can be used as an integrator with the appropriate choice of cut off frequency. Since this approach requires less computational effort, in case of using digital environments such as low memory MCUs and eliminates the use of open loop integrators it is adopted in the application. The model of a low pass filter in frequency domain is shown in (5.5). If the filter time constant $\tau$ is chosen big enough, and it behaves as $\tau \gg 1$ the filter will behave like an approximate integrator with a gain. Using this property, low pass filters are used to integrate the calculated back EMFs in order to calculate the flux linkages $\lambda_\alpha$ and $\lambda_\beta$ which will eventuate with estimated flux linkage values in an open loop manner.

$$\frac{1}{1 + \tau s} \tag{5.5}$$

The block diagram of the flux estimation is shown in Figure 31. As can be seen the phase currents are measured through three shunt resistors and then the back EMF is calculated. By using two low pass filters the back EMF is integrated and the flux linkages are obtained [10]. It should be noted that an open loop pure integration is sensitive against any errors or peaks in voltage equations, which are caused by drift, in order to prevent issues that can be caused because of this sensitivity, a low pass filter, can be used [23]. In addition to low computational effort, preventing the sensitivity that might occur because of the use of pure integrator structures is another reason to use low pass filters for integration.

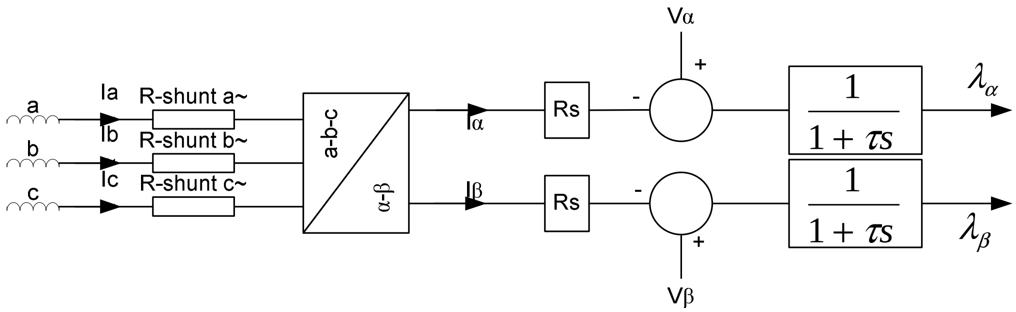


**Figure 31:** Block diagram of open loop flux linkage estimation.

It should be noted that using open loop flux linkage estimation method also has disadvantages since it sensitive to voltage errors e.g. at low speeds, voltage drops in electronic parts, DC Bus voltage fluctuations or any increase/decrease in the stator resistance value [7].

### 5.3.2 Position estimation

The position or phase estimation of the rotor depends on the open loop flux linkage estimations. As shown in (4.18) flux linkages in α-β reference frame depends on the phase of the system, meaning the position of the rotor. The rotor position can be estimated using the estimated flux linkage values and the identities shown in (4.18). Considering the flux linkages are dependent on system phase, vice versa can be implemented. The Flux linkage equations can be re-ordered and written as in (5.6) and (5.7) respectively.

$$\lambda_\alpha - LI_\alpha = \Lambda_m \cos(\theta) \tag{5.6}$$

$$\lambda_\beta - LI_\beta = \Lambda_m \sin(\theta) \tag{5.7}$$

In the application prototype, the system phase $\theta$ is estimated using equations (5.6) and (5.7). In order to obtain $\theta$ the equations can be re-ordered again as shown in (5.8) and (5.9)

$$\frac{\lambda_\beta - LI_\beta}{\lambda_\alpha - LI_\alpha} = \frac{\Lambda_m \sin(\theta)}{\Lambda_m \cos(\theta)} \tag{5.8}$$

$$\frac{\lambda_\beta - LI_\beta}{\lambda_\alpha - LI_\alpha} = \tan(\theta) \tag{5.9}$$

After re-ordering the equations $arctan$ of the left hand side of the equation (5.9) will give us the system phase $\theta$. The system phase can be obtained as shown in (5.10)

$$\theta = arctan\left(\frac{\lambda_\beta - LI_\beta}{\lambda_\alpha - LI_\alpha}\right) \tag{5.10}$$

The position found in (5.10) is the phase of the field in the respective control interrupt, so it is defined in stator reference frame. In order to use it as position feedback, it should be transformed in to rotor reference frame, which can be done as shown in (5.11). Where $\theta_r$ the position of the rotor in rotor reference is frame and $p$ is the number of pole pairs.

$$\theta_r = \frac{\theta}{p} \tag{5.11}$$

### 5.3.3 Speed estimation

With the system phase, being the phase of the stator field estimated the rotor speed can be estimated relatively easier. With speed being the first derivative of position with respect to time in mind, the estimation of the rotor speed in the application prototype, a derivative scheme is formed and the frequency of the field is obtained as shown in (5.12).

$$\omega = \frac{d\theta}{dt} \tag{5.12}$$

Since the calculation of the frequency is made using a MCU, which is a digital environment, the derivative is taken by making use of derivative in discrete time. The derivative scheme used in the application is shown in (5.13).

$$\omega = f_s(\theta(k+1) - \theta(k)) \tag{5.13}$$

Where ω is the stator field's rotation frequency, $f_s$ is the sampling time, which corresponds to control interrupt frequency, $\theta(k+1)$ is the position of the rotating field in the $(k+1)^{th}$ interrupt, and $\theta(k)$ is the position of the rotating field in the $(k)^{th}$ interrupt. From this point on in order to derive the rotor's speed estimation, the frequency found in (5.15) should be transformed in to rotor reference frame. Frequency value, which is in rad/s, should also be transformed in to rpm. This can be done as shown in (5.14).

$$n_r = \frac{60}{2\pi p}\omega \tag{5.14}$$

With flux linkages, position and speed estimated, a general block diagram for estimation process can be formed. The block diagram given in Figure 32 shows the estimation process with that is used in the application prototype for state feedbacks and transformation feedbacks.

### 5.4 Critical Control Regions

In the application, the experiments performed showed that there are two critical operating regions for vector control. In these regions, the dynamics of the system is either, too hard to control or impossible because of the chosen control strategies and estimation methods. These control regions can be named the start up region and the field-weakening region. The problems, solution approaches and the effects on system dynamics and response are examined in detail.

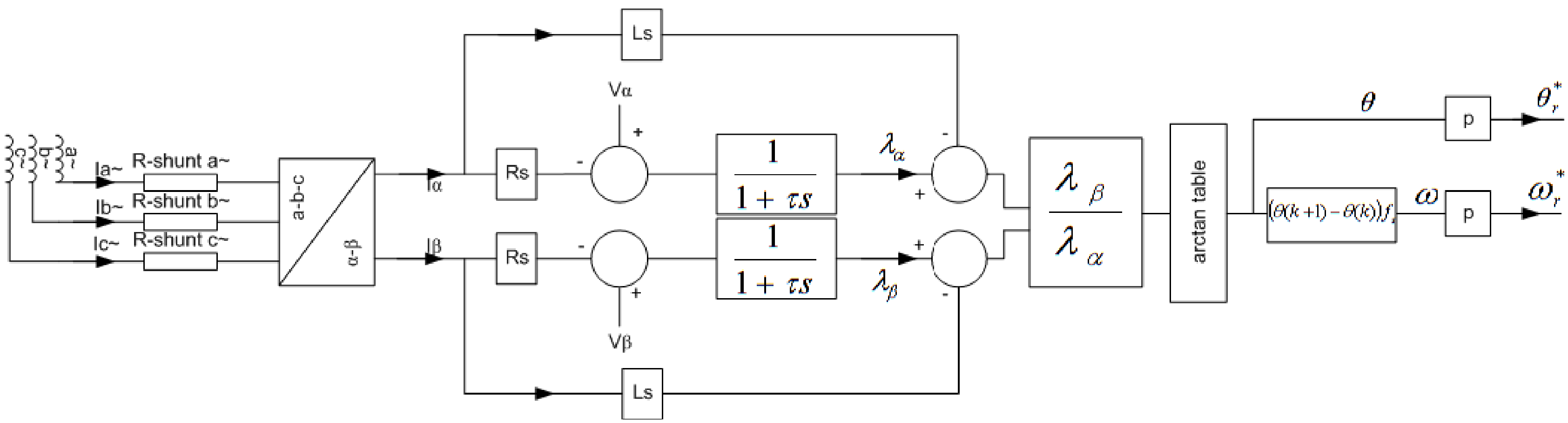


**Figure 32:** Estimation process block diagram.

### 5.4.1 Start up

Start up operating region is the region where the motor is at stand still state and just energized in order to reach a speed reference. However, with the adopted estimation methods there is a problem at start up operating region. At start up and very low speed values of rotor, the generated back EMF is not high enough to make correct position and speed estimations [9]. This is highly due to the fact that BUS voltage being low and the voltage drops through the supply circuit and inverter topology makes the back EMF even smaller. Moreover, low frequency operation lowers the bandwidth of the estimator structure and the disturbance resistance. That is why different approaches for control should be applied in low frequency region such as start up.

There are mainly two kinds of control approaches for the start up control of a non-salient PMSM. The first one would be the use of a low-resolution type position sensor such as Hall Effect sensors in order to sense the initial position of the rotor [9]. Even though it is a reliable way to estimate the initial position, the approach using Hall Effect sensors is not desired in this particular application since the system was initially designed to be sensorless.

The second approach would be using an open loop start up control algorithm which was the approach adopted for this particular application covered in the thesis. In the open loop start up control scheme, the speed control loop is opened and the speed reference is not compared with the speed feedback since the estimation cannot be evaluated correctly. In such cases, one approach would be to supply one or two phases of the motor and have the rotor align itself firstly, and then have the rotor accelerate with a constant rate until a speed value on which the back EMF can be estimated correctly. However, this approach does not have good dynamical control and performance in addition to not being able to provide the initial position of the rotor [7].

Washing machine operation in particular, must start reliably but on the other hand, does not require full torque control at stand still in addition to not requiring the initial position [21]. With this said, it is appropriate to say that the use of second approach with open loop speed control in the stand still operation range is possible in washing machines.

In the open loop start up scheme, the rotor is firstly aligned by imposing a magnetizing current on the windings, which produces a stationary field and has the rotor locked at an arbitrary initial position with a non-rotating field [24]. The second step of the scheme is to apply a speed reference in open loop control with a fixed acceleration rate until the motor reaches to a predetermined speed value on which the back EMF is large enough to estimate [25]. The speed reference and the magnetization current reference that is used in the particular application are given in Figure 33. Moreover, the start up control can be illustrated as in Figure 34; as can be seen a speed reference with a fixed acceleration rate is used that generates an exponential position scheme.

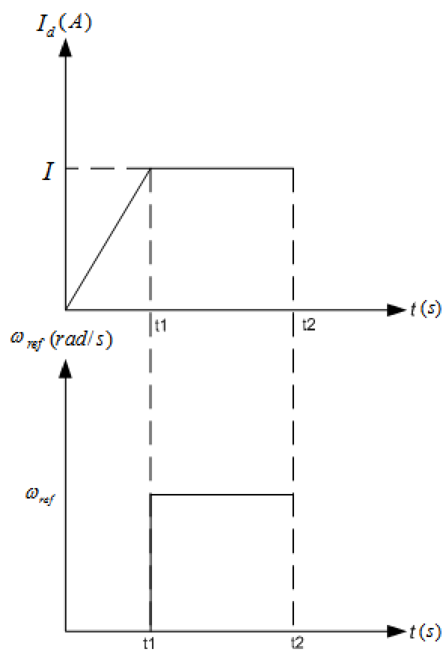


**Figure 33:** $\boldsymbol{I_d}$ and $\boldsymbol{\omega_{ref}}$ profile in start up region.

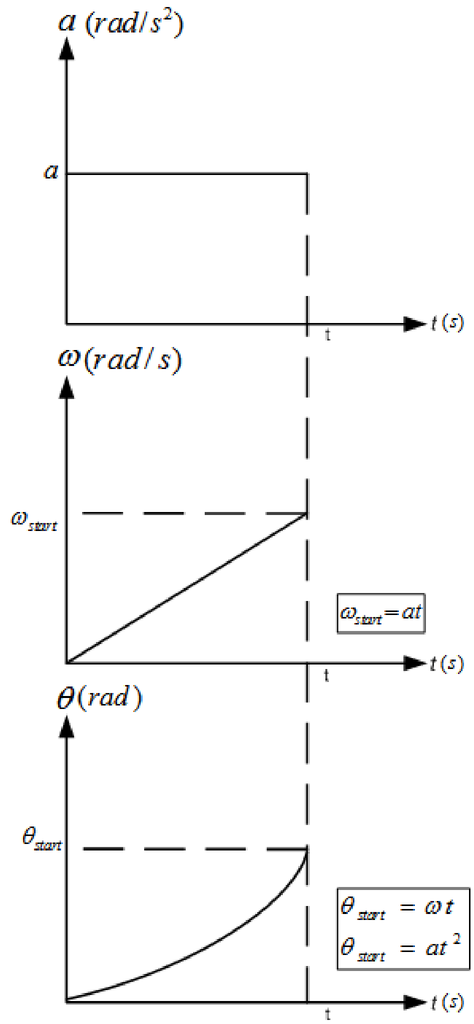


**Figure 34:** Acceleration, speed and position characteristics in start up.

### 5.4.2 Field weakening

Washing machine application is particularly challenging because of torque speed characteristics, which has a very wide operation speed region requiring very high torque at wash cycle and very high speed at spin cycle [21]. Since motors with very high nominal speeds such as 15000-20000 rpm are not produced for appliance industry, a different control approach should be adopted in order to have the motor reach this speed to extract the maximum amount of water from the laundry [26].

This operation is achieved with a control scheme named field weakening or flux weakening in vector control algorithm. There is a need for field weakening operation not only because of low nominal speed values but also the maximum DC Bus and motor input voltage and currents are limited with the compenents' physical limits. At the maximum use of DC Bus voltage, the motor will reach its rated speed and for speeds higher than the rated speed, field weakening must be applied [8]. Here, the basic task is to keep the flux value at a constant level in order to prevent exceeding the maximum DC Bus voltage [4].

In field weakening region, the air gap flux is reduced by creating a magnetic field that opposes the magnetic field of the stator. With that done, using same DC Bus voltage, the air gap flux will decrease and the speed of the motor will be able to increase. This can be done with several control schemes, which are model free, or model based. Model free control schemes can be named as adaptive and six step control schemes; whereas model based schemes can be named as direct or indirect control of the flux. [8].

In the particular application of vector control of PMSM in washing machines, control scheme used for field weakening operation is the indirect control of the flux. In indirect control scheme, the magnetizing flux is controlled indirectly by using the magnetizing current component $I_d$. In order to create an opposing field that will reduce the air gap flux, again, two control approaches being open loop and closed loop can be used.

In open loop field weakening control, the $I_d$ current is controlled in an open loop manner by tabulating the required $I_d$ values over the speed region while in closed loop field weakening control, $I_d$ current is regulated by making use of DC Bus voltage and the motor supply voltages. The open loop field weakening control is a pretty straightforward way to implement the control scheme; however, it requires exact values for magnet flux and motor inductance which may vary [21]. Thus, the closed loop approach is adopted in the application.

In closed loop approach, DC Bus voltages and the motor supply voltages are compared. At a value, where motor supply voltage exceed the DC Bus voltage value, field weakening operation are started. By making use of the ratio between the two voltage values, the $I_d$ current is regulated with a negative sign which will produce a controlled demagnetizing field opposing the air gap flux and making it possible to reach higher speeds than rated speed value in a more robust manner [21]. The important point here is to taking note that, applying a negative current in the magnetizing component always has a possibility of demagnetizing the permanent magnets, thus this scheme is generally not used for speed values that is higher than three times of the rated speed value.

### 5.5 Control Scheme Overview

With the adoption of open loop start up procedure and field weakening control in the application, it is both made possible to operate in zero speed and very high speeds which is a required characteristic of the washing machine. In the said application, all of these control routines are done in a single control interrupt.
The details of the control interrupt can be summarized in five steps as follows:

STEP 1: Current measurements

STEP 2: Rebuilding flux linkages

STEP 3: Estimating the position and speed

STEP 4: Regulating the voltage values in d-q axis by making use of speed reference and d-axis current reference

STEP 5: Calculating a duty cycle by making use of voltage values found in STEP 4, and creating PWM signals that will be used to drive the inverter circuit.

An example for the main control interrupt is shown in Figure 35 for a single shunt current sensing structure that is introduced in [10]. Our particular application uses a very similar structure, which is equipped with three shunt resistors in order to achieve the current sensing.

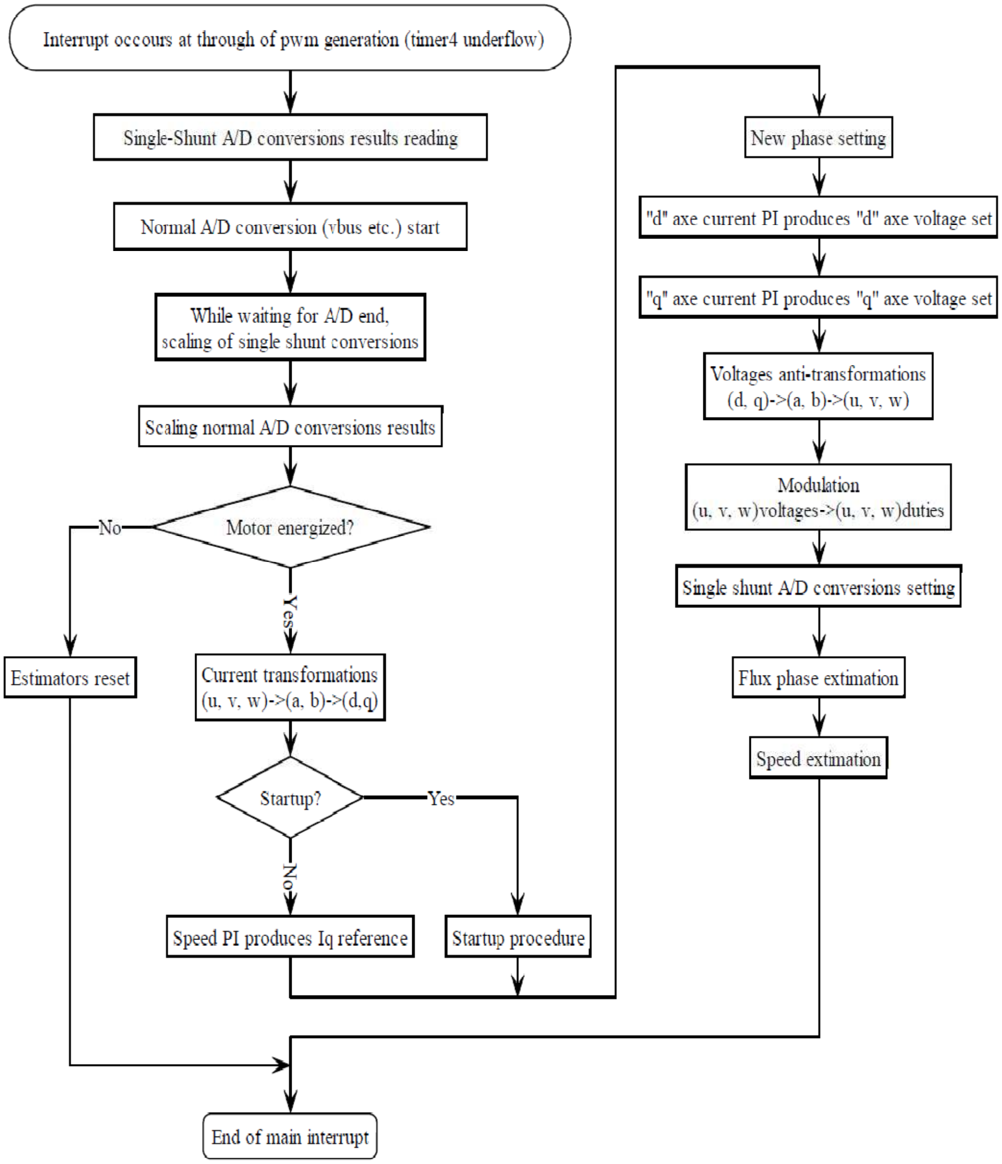


**Figure 35:** An example flowchart for the main control interrupt.

# 6. CONTROL LOOPS and PROPOSED CONTROLLER TUNING METHOD

When designing a control structure for a particular system, one should consider the system dynamics and what is expected from the system. In terms of washing machine operation, the control system is expected to be simple even though it should provide sufficient amount of flexibility in the production of the washing machine. The flexibility is needed because of the fact that in the production process, each and every washing machine cannot be identical because of the tolerance levels of the components. Thus, the control structure should accommodate to these variances occurring due to offline and online parameter changes [27].

## 6.1 Introduction of Control Loops

It is stated that in vector control scheme of a PMSM there are three control loops. The first control loop is the speed control loop, which produces an $I_q$ reference by comparing the speed reference and estimated speed value. The second control loop is the control loop of $I_q$ which is referred as the torque control loop which produces a $V_q$ reference by comparing the $I_q$ reference value and the measured $I_q$ value. The last control loop in a vector control structre is the control loop of $I_d$ which is referred as field control loop. In Figure 36, control loops in a vector control structure is shown in detail.

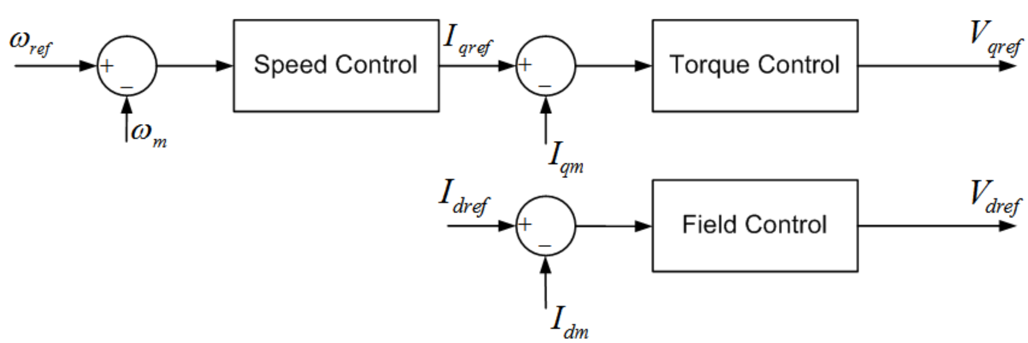


**Figure 36:** Control loops in vector control.

Generally, for both speed and current control loops of motor control applications probably the most cost effective control structure used in industry is PI type controllers since they are easy to implement, robust and provide good dynamical results when tuned properly. However, these types of controllers are used and effective when the mathematical model of the system can be considered linear. The vector control application makes it possible to use linear controller structures such as PI by transforming the mathematical model of the motor in to a scheme that is very similar to the model of a DC motor which can be considered linear under some assumptions.

In addition to PI type controllers, there are other approaches that can be adopted for speed and current controllers of a vector control scheme. For example, adaptive control schemes such as artificial neural networks can be implemented. But in appliances, a product having an intelligent type of control scheme can be considered unreliable. Moreover, these kinds of intelligent control schemes generally require powerful processors with a good computational performance. But the processors and microcontrollers used in appliances are chosen from the low cost, simple processor segments due to their low prices. Because of these reasons PI type controllers are preferred.

### 6.2 Tuning Approaches

In the application two types of controller tuning approaches are used for PI type controllers. The first approach adopted was to tune the proportional and integral terms of the controllers with empirical methods and the second approach adopted within the scope of the thesis on tuning the parameters of the controllers is to use an optimization algorithm, which will adaptively tune the PI parameters online. The details will be provided in the following section on the tuning of the PI parameters.

#### 6.2.1 Tuning by empirical means

When PI type linear controllers are of concern, it should be noted that the tuning might be problematic. A widely used empirical and systematical approach for tuning of PI type controller in practical applications without making use of mathematical tuning algorithms consists of three steps.

> STEP 1: Setting the integral term of the PI controller and increasing the proportional term until the system response oscillates
>
> STEP 2: Setting the proportional term to approximately half of the value found in STEP 1

STEP 3: Increasing the integral term until the steady state error is in an acceptable range.

This tuning method is used widely; however, it is not appropriate for most of the systems where online tuning is required. Since the system is made to oscillate, this oscillation can cause unwanted effects on the system. In this application tuning cannot be done using this particular tuning algorithm because the washing machine should be energized and oscillations in speed and current would affect the system critically.

In this particular study the first approach adopted was to tune the proportional and integral terms of the controllers by means of empirical tuning methods. Even though it ends up with a satisfactory performance of the overall system, this approach is a time consuming approach because there are different operating regions in a whole washing machine operation, which have different dynamics, requiring different controller terms. That is why tuning PI controllers by means of empirical methods is not an easy task since when washing machines are of concern it is a known fact, which is also stated before, that they have different load and speed characteristics in different regions with variable load characteristics and the controllers should be able to adapt all these changes. In order to meet these variable system dynamics, the proportional and integral terms of each controller structure is tabulated in respective operating regions, which is even more time consuming than just empirically tuning the controllers once.

### 6.2.2 Adaptive online tuning approach

The adaptive online tuning approach is the second approach used in order to tune the PI parameters within the scope of this study. The adaptive approach is equipped with an optimization algorithm, which is used to achieve the online tuning of the PI parameters by monitoring the respective error values. The particular optimization algorithm is chosen as Nelder-Mead optimization algorithm.

The reason behind the choice of Nelder-Mead optimization algorithm can be explained with its main advantage of needing little computational power. This reflects to the cost of the overall system since, it does not require a powerful processor with more memory.

Nelder-Mead optimization algorithm can be described as a direct search method which can be applied without the need of a process model. The only inputs of the algorithm are some measurements needed for the respective optimization operation. Also, it is a widely used algorithm particularly in chemical processes because of its simplicity and efficiency [28]. The original algorithm consists of six steps that can be shown as a pseudo algorithm below:

*STEP 1: Define the initial simplex parameters* $x_1, x_2, x_3, x_4$ *and evaluate respective objective function values* $f(x_1), f(x_2), f(x_3), f(x_4)$*,*

*STEP 2: Sort the evaluated objective function values and calculate the simplex's centroid (6.1) with the values except the worst value.*

$$c = (x_{best} + x_{2ndbest} + x_{2ndworst})/3 \tag{6.1}$$

*STEP 3: Reflect the worst point with respect to the centroid. (6.2)*

$$x_r = c + \alpha(c - x_{worst}) \tag{6.2}$$

*IF The reflected point is better than the best, GO TO STEP 4*

*ELSE IF The reflected point is better than the second worst but not better than the best; replace the worst point by reflected point and GO TO STEP 1.*

*ELSE GO TO STEP 5.*

*STEP 4: Expand the worst point with respect to the centroid. (6.3)*

$$x_e = c + \gamma(c - x_{worst}) \tag{6.3}$$

*IF The expanded point is better than the best, replace the worst point with expanded point and GO TO STEP 1.*

*ELSE replace the worst point with reflected point and go to STEP 1.*

*STEP 5: Contract the worst point with respect to centroid. (6.4)*

$$x_c = x_{worst} + \rho(c - x_{worst}) \tag{6.4}$$

*IF the contracted point is better than the worst point, replace worst point with the contracted point and GO TO STEP 1.*

*ELSE GO TO STEP 6.*

*STEP 6: Reduce all the points except the best and GO TO STEP 1. (6.5)*

$$x_{red} = x_{best} + \sigma(x_i - x_{best}), i = \{2^{nd}best, 2^{nd}worst, wors\} \tag{6.5}$$

When the algorithm is examined, the simple structure and the small number of elemental calculations can be seen. Even though the method has advantages such as simplicity and few function evaluations without making use of derivatives, it is known to get stuck especially if the initial simplex is not chosen properly or the optimum point is moving [28]. Such importance on initial conditions is not a desired property for an optimization algorithm which brings the downfall of Nelder-Mead method. However, if one can imagine a system that is semi-tuned, this initial condition disadvantage does not exist. With this assumption in mind, it could also be assumed that in washing machine control structure which was tuned just enough to have the motor operate is a necessary set point for the initial simplex parameters for this particular algorithm.

In addition, if it is desired to use Nelder-Mead optimization algorithm in an online tuning structure, one should make further modifications to prevent the algorithm being stuck or create computational load by over-iterating after an optimum point is found. An example approach for such a goal might be to limit the simplex dimensions along with properly choosing the initial simplex. This can be done by using the values found during the empirical tuning.

In the application step for the algorithm, an empirical tuning is applied in order to have the motor operate in a particular operating region. After finding an approximate value for current PI gains by means of empirical tuning, the algorithm is established in the experiment environment and programmed in to the motor control MCU of the washing machine. The algorithm then is used online to fine tune these control parameters to have the system adapt load and parameter changes better and consequently building a robust semi-adaptive control scheme. The general flow chart of the application is given in Figure 37.

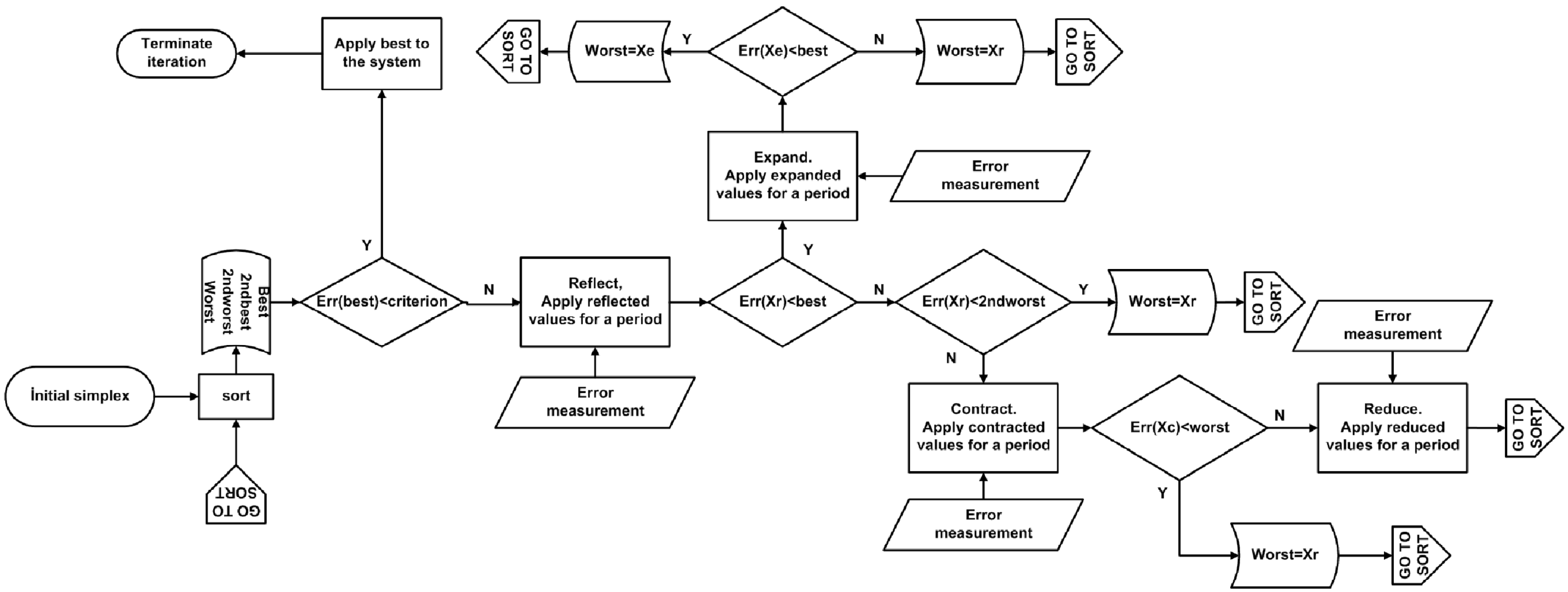


**Figure 37:** Flowchart of Nelder-Mead optimization algorithm's application.

Since the experiments are done in a real washing machine, some counter measures are also taken. In addition to limiting the simplex over the iterations to prevent over-iterations an approximate performance measure for the algorithm is determined. Used performance measure J is given in (6.6) which correspond to the integral of the absolute value of q-axis current error and d-axis current error for respective PIs. This performance measure is chosen so that the negative and positive errors in a time period can be collected and to provide a robust control. Iterations are terminated when the performance measure reaches a desired performance criterion given in (6.7) which is also chosen approximately.

$$J = \int_{0}^{t} |e| dt \tag{6.6}$$

$$J \leq I/20 \tag{6.7}$$

The reason for using such a performance measure is to ensure the robustness of the system for all load conditions that might occur specially in wash cycle. The washing machine load is never constant. Even when the drum is empty there are mechanical unbalances which cause torque to fluctuate and effect the current measurements. In order to ensure a more robust control while calculating the error values of currents, certain PI parameters are applied to the system for a time period and the integral of the absolute value of the error is computed.

Experiments are performed for both empirically tuned PI controlled washing machine and the adaptively tuned PI controlled washing machine in the experiment environment and the data are gathered for different operating regions of the washing machine with different amounts of loads. The data and the evaluation of the results is made in the following chapter.

## 7. EXPERIMENTAL RESULTS

Experiments are performed for both emprically tuned and adaptively tuned PI controller structures in two different working conditions. First set of experiments are done in order to investigate the effectiveness of the algorithm in the washing cycle and the second set of experiments are done in order to investigate the effectiveness of the algorithm in spin-dry cycle. The data are gathered for two different load conditions in both wash cycle and spin-dry cycle. The first load condition for wash cycle is empty drum and the second load condition is a drum wth 4kg laundry. As for spin-dry cycle first load condition is also empty drum and second load condition is 500g unbalanced load. All experiments concerning wash cycle are performed for 415 rpm motor speed whereas the experiments concerning wash cycle are performed for 6500 rpm motor speed.

### 7.1 Experimental Results for Empirically Tuned PI Controllers in Wash Cycle

In wash cycle, the important quantity to control is torque production since the load torque is high and the motor is in a constant start-stop operation. Since the quantity that is critical for torque control is the q-axis current $I_q$, the data in wash cycle is gathered with regards to $I_q$. The reference and the error data for $I_q$ is gathered.

In addition the effect of tuning only current PI controllers and regulating the dynamical performance of the motor on speed response is also examined. Thus, speed reference and error data are gathered.

Concerning the empirical tuning, the gain values for PI controllers in wash cycle is chosen as 200 for each gain after a set of experiments in order to choose the appropriate gain.

#### 7.1.1 Unloaded drum

A set of experiments with unloaded drum is performed in order to create comparison probability for the performance of the optimization algorithm and tuning method for relatively small amounts of laundry. The experiments are performed for $K_p = 200$ and $K_I = 200$ which are values empirically found. The drum is rotated empty with a speed of 50 rpm, which results as 415 rpm motor speed.

The $I_q$ reference and error data is plotted and given in Figure 38 whereas the speed reference and error is plotted and given in Figure 39.

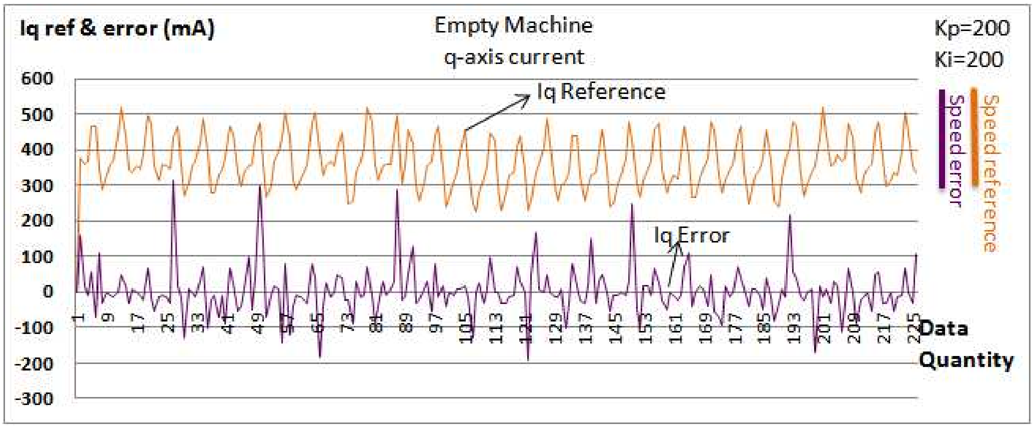


**Figure 38:** $\boldsymbol{I_q}$ reference and error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 200}$ and $\boldsymbol{K_I = 200}$ in wash cycle.

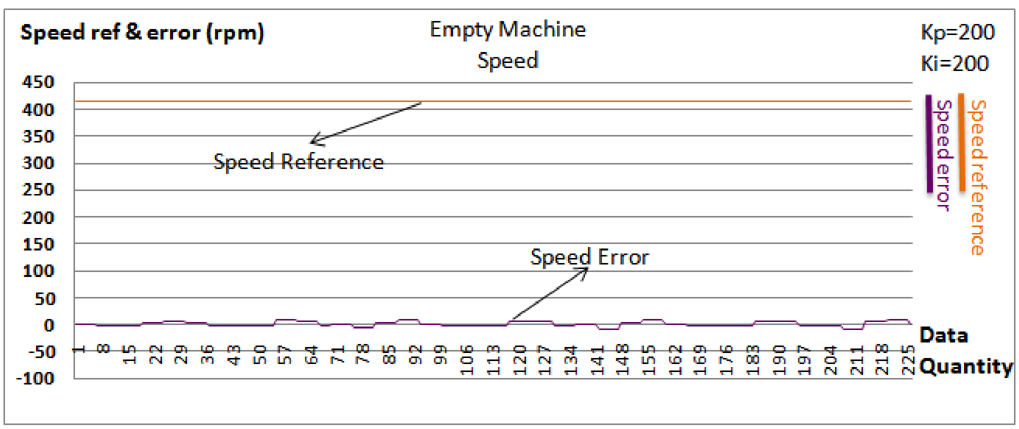


**Figure 39:** Speed reference and error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 200}$ and $\boldsymbol{K_I = 200}$ in wash cycle.

### 7.1.2 Loaded drum

After the experiments are performed with an unloaded drum, experiments with a drum that is loaded with 4 kg of laundry is performed for same speed references and same proportional and integral gains for current PI controllers. The said speed reference for motor is 415 rpm and the proportional and integral terms' gains of current PI controllers are 200 each, which is a value that is empirically found.

The gathered data is shown in Figure 40 and Figure 41 for $I_q$ reference and error and Speed reference and error respectively.

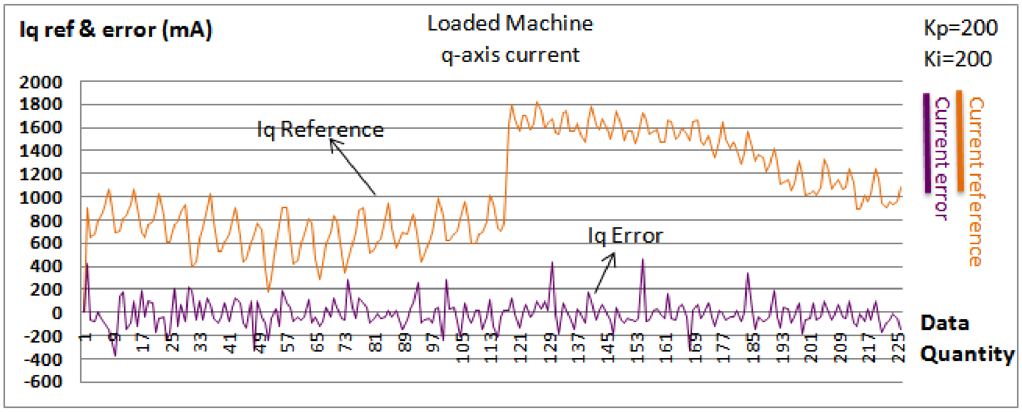


**Figure 40:** $\boldsymbol{I_q}$ reference and error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 200}$ and $\boldsymbol{K_I = 200}$ in wash cycle.

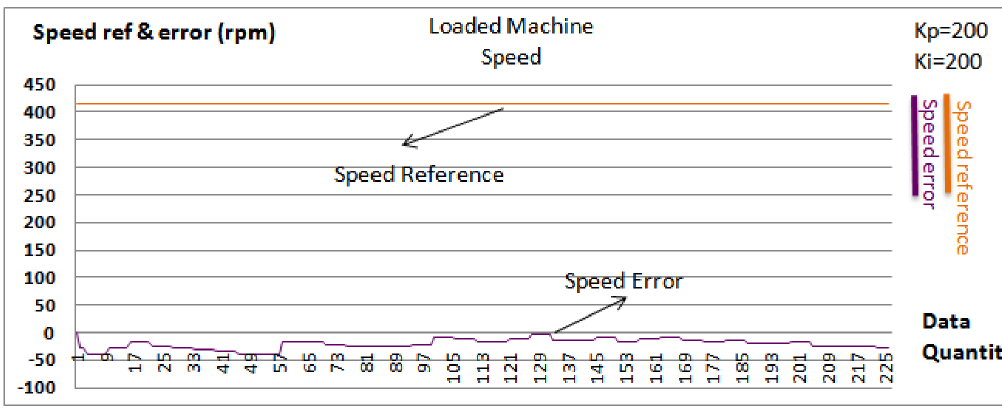


**Figure 41:** Speed reference and error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 200}$ and $\boldsymbol{K_I = 200}$ in wash cycle.

### 7.2 Experimental Results for Adaptively Tuned PI Controllers in Wash Cycle

This tuning scheme's details are explained in chapter 6. The tuning is done after an empirical value for each PI gain of current controllers are chosen. The tuning then, iterates these gains by putting a tolerance on them and searches for a optimized PI gain. The initial simplex is formed by adding and subtracting some tolerances on the empirically found PI coefficients. These tolerances are chosen as, $\pm 20$ and $\pm 40$ resulting with 4 sets of PI gains listed below.

- $K_p = 220, K_I = 220$

- $K_p = 240, K_I = 240$

- $K_p = 180, K_I = 180$

- $K_p = 160, K_I = 160$

After the initial simplex is chosen, the algorithm is left to converge to an error value that is in the defined performance index and has a better dynamical performance, this operation is done by gathering data for a period of time that is meaningful when the speed and torque characteristics of wash cycle is considered. In terms of wash cycle this time period for data gathering is chosen as 10 seconds. The data for error value gathered for 10 seconds and then the performance index $J = \int_0^t |e|dt$ is calculated in order to perform or stop the iterations. This calculation is done in every iteration of the simplex.

### 7.2.1 Unloaded drum

A set of experiments with unloaded drum is performed with the optimization algorithm executed. At the end of the optimization algorithm the calculated values for the PI coefficients are found as $K_p = 150$ and $K_I = 140$. The drum is rotated empty with a speed of 50 rpm, which results as 415 rpm motor speed.

The gathered data is shown in Figure 42 and Figure 43 for $I_q$ reference and error and Speed reference and error respectively.

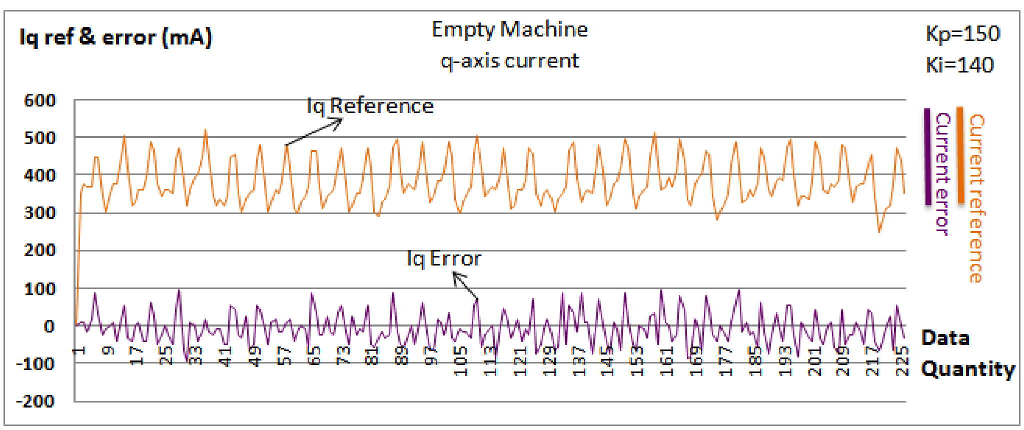


**Figure 42: $I_q$** reference and error data for unloaded washing machine with current PI controller coefficients of $K_p = 150$ and $K_I = 140$ in wash cycle.

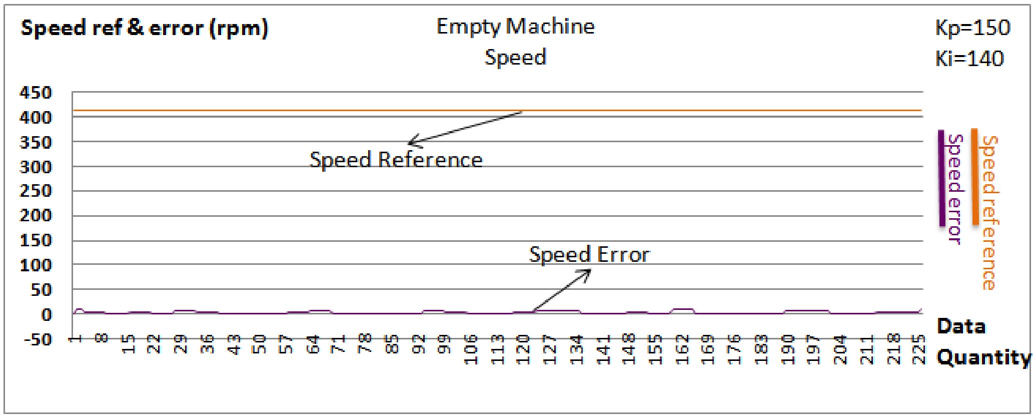


**Figure 43:** Speed reference and error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 150}$ and $\boldsymbol{K_I = 140}$ in wash cycle.

### 7.2.2 Loaded drum

After the experiments are performed with an unloaded drum, experiments with a drum that is loaded with 4 kg of laundry is performed but the algorithm is executed once again and it is waited for it to converge to an optimum value before tha data are gathered. The speed reference used for this experiment was the same as the other experiments. The optimized values of the current PI controllers' gains are calculated by Nelder-Mead optimization algorithm and found as $K_p = 142$ and $K_I = 130$. The drum is rotated loaded with a speed of 50 rpm, which results as 415 rpm motor speed. The gathered data is shown in Figure 40 and Figure 41 for $I_q$ reference and error and Speed reference and error respectively.

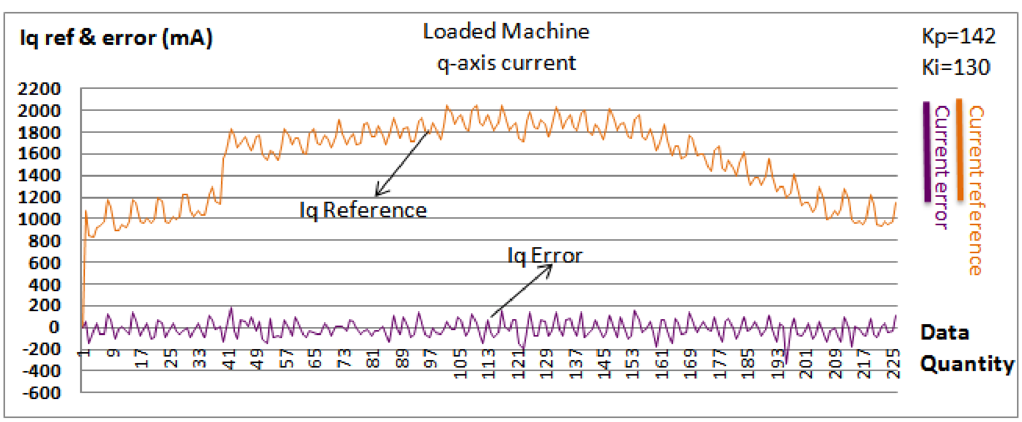


**Figure 44:** $\boldsymbol{I_q}$ reference and error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 142}$ and $\boldsymbol{K_I = 130}$ in wash cycle.

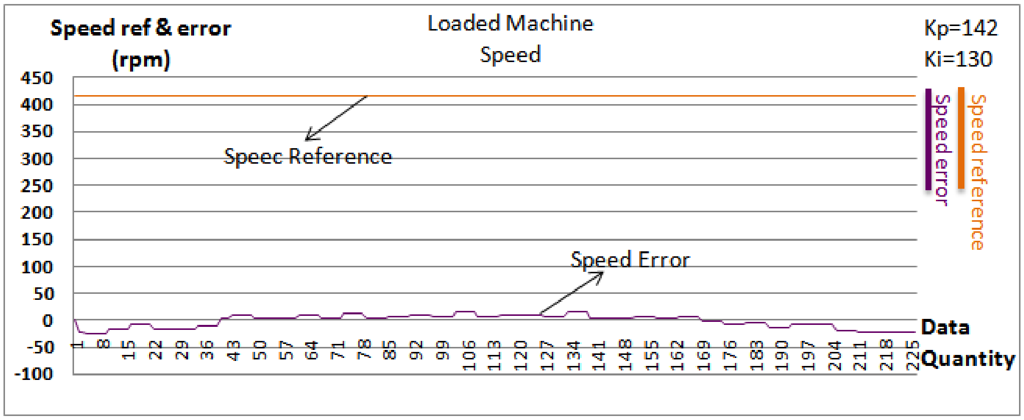


**Figure 45:** Speed reference and error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p} = \mathbf{142}$ and $\boldsymbol{K_I} = \mathbf{130}$ in wash cycle.

## 7.3 Experimental Results for Empirically Tuned PI Controllers in Spin-Dry Cycle

The proper control of currents is also crucial in spin-dry cycle which is done in field weakening region. With poor control on current PIs one might cause the motor become unstable. Experiments concerning spin-dry cycle is done using 6500 rpm motor speed, which is a region that is close to a critical drum speed used in spin-dry operation. Also, this speed value is close to the mechanical resonancy frequency of the system and this extend the criticalness of the speed region. Once the motor can pass this speed limit it is observed that it can reach the full speed with no change in the PI coefficients.

Since the quantity that is critical for torque control is the q-axis current $I_q$, the data in wash cycle is gathered with regards to $I_q$. The reference and the error data for $I_q$ is gathered.

In addition, the effect of tuning only current PI controllers and regulating the dynamical performance of the motor on speed response is also examined. Thus, speed reference and error data are gathered.

### 7.3.1 Unloaded drum

The experiments are performed assuming the operation is not stopped after the experiments with lower speeds. Consequently the initial PI parameters are chosen as $K_p = 142$ and $K_I = 130$, which are the results of the latest iteration performed in wash cycle. The motor is spinned at 6500 rpm at first and data is gathered with the mentioned PI coefficients. The $I_q$ reference and error data is plotted and given in Figure 46, whereas the speed error is plotted and given in Figure 47.

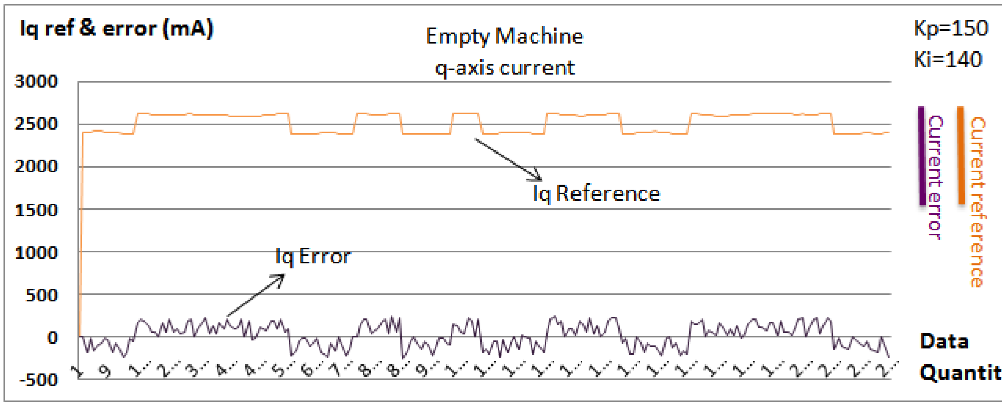


**Figure 46:** $\boldsymbol{I_q}$ reference and error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 150}$ and $\boldsymbol{K_I = 140}$ in spin-dry cycle.

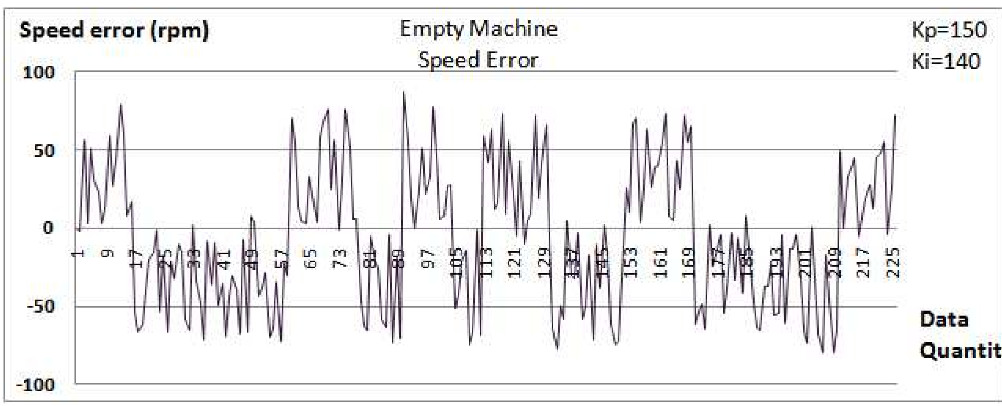


**Figure 47:** Speed reference and error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 150}$ and $\boldsymbol{K_I = 140}$ in spin-dry cycle.

### 7.3.2 Loaded drum

After the experiments are performed with an unloaded drum, experiments with a drum, that is loaded with 500 g of unbalanced load is performed for same speed references and same proportional and integral gains for current PI controllers. The said speed reference for motor is 6500 rpm and the proportional and integral terms' gains of current PI controllers are 150 and 140 each.

The gathered data is shown in Figure 48 and Figure 49 for $I_q$ reference and error and Speed reference and error respectively.

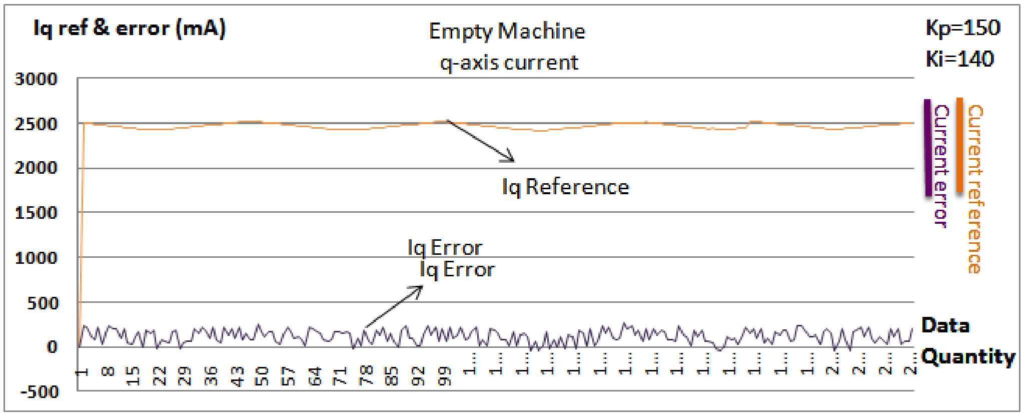


**Figure 48:** $I_q$ reference and error data for loaded washing machine with current PI controller coefficients of $K_p = 150$ and $K_I = 140$ in spin-dry cycle.

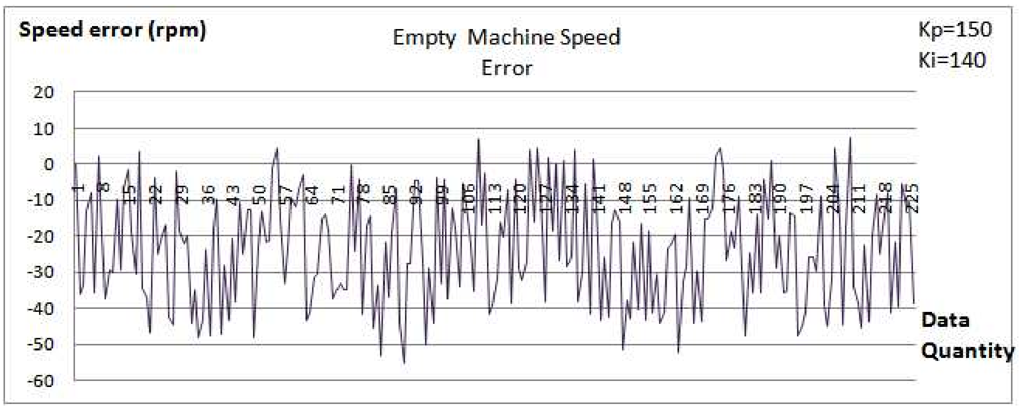


**Figure 49:** Speed reference and error data for loaded washing machine with current PI controller coefficients of $K_p = 150$ and $K_I = 140$ in spin-dry cycle.

## 7.4 Experimental Results for Adaptively Tuned PI Controllers in Spin-Dry Cycle

The tuning algorithm is run after the motor reaches a steady state speed value of 6500 rpm which was the reference speed. The tuning structure is the same as the one used in wash cycle which iterates the gains obtained by putting a tolerance on the given PI coefficient that is taken as $K_p = 150$ and $K_I = 140$ for this case. And the algorithm then searches for an optimized PI gain. The initial simplex is formed by adding and subtracting some tolerances on PI coefficients taken from the wash cycle data. These tolerances are chosen as, $\pm 20$ and $\pm 40$ resulting with 4 sets of PI gains listed below.

- $K_p = 170, K_I = 160$

- $K_p = 190, K_I = 180$

- $K_p = 140, K_I = 130$

- $K_p = 120, K_I = 110$

After the initial simplex is chosen as above, the algorithm is left to converge to an error value that is in the defined performance index and has a better dynamical performance, this operation is done by gathering data for a period of time that is meaningful when the speed and torque characteristics of wash cycle is considered. In terms of spin-dry this time period for data gathering is chosen as 1 seconds. The data for error value gathered for 1 seconds and then the performance index $J = \int_0^t |e|dt$ is calculated in order to perform or stop the iterations. This calculation is done in every iteration of the simplex.

### 7.4.1 Unloaded drum

A set of experiments with unloaded drum is performed with the optimization algorithm executed. At the end of the optimization algorithm the calculated values for the PI coefficients are found as $K_p = 150$ and $K_I = 140$. The drum is rotated empty with a speed of 50 rpm, which results as 6500 rpm motor speed.

The gathered data is shown in Figure 50 and Figure 51 for $I_q$ reference and error and Speed reference and error respectively.

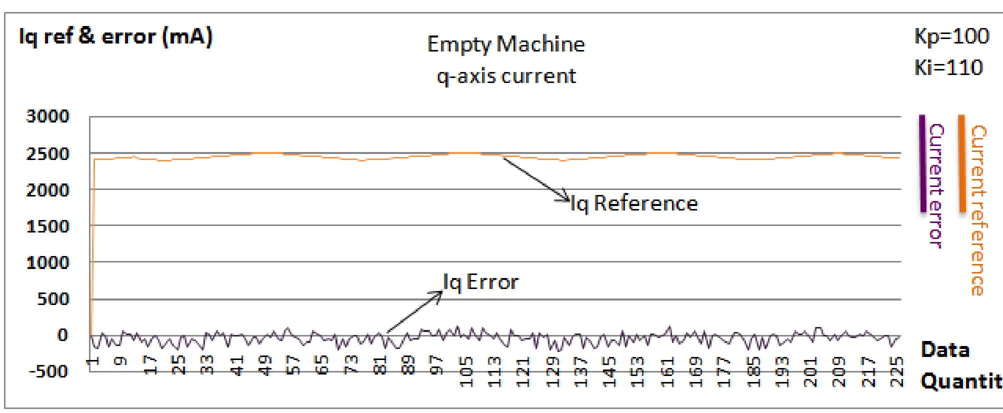


**Figure 50:** $I_q$ reference and error data for unloaded washing machine with current PI controller coefficients of $K_p = 100$ and $K_I = 110$ in spin-dry cycle.

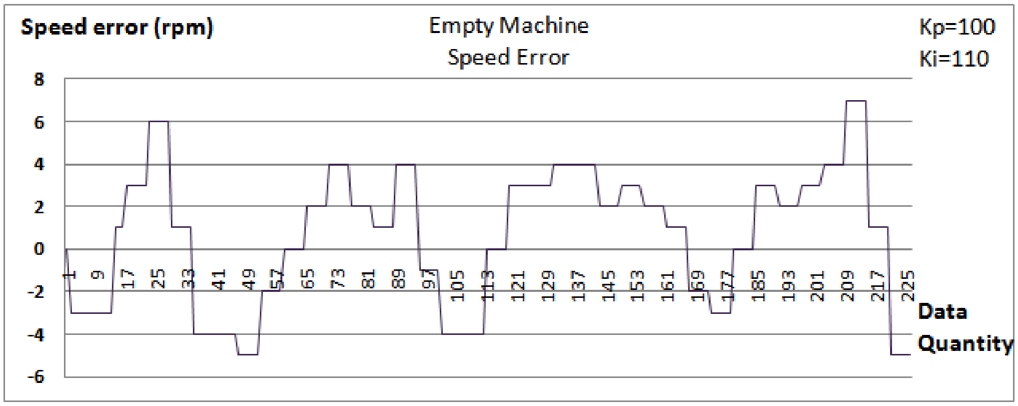


**Figure 51:** Speed error data for unloaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 100}$ and $\boldsymbol{K_I = 110}$ in spin-dry cycle.

### 7.4.2 Loaded drum

After the experiments are performed with an unloaded drum, experiments with a drum that is loaded with 500 g of unbalanced load is performed but the algorithm is executed once again and it is waited for it to converge to an optimum value before tha data are gathered. The speed reference used for this experiment was the same as the other experiments which is 6500 rpm. The optimized values of the current PI controllers' gains are calculated by Nelder-Mead optimization algorithm and found as $K_p = 142$ and $K_I = 130$. The gathered data is shown in Figure 52 and Figure 53 for $I_q$ reference and error and Speed reference and error respectively.

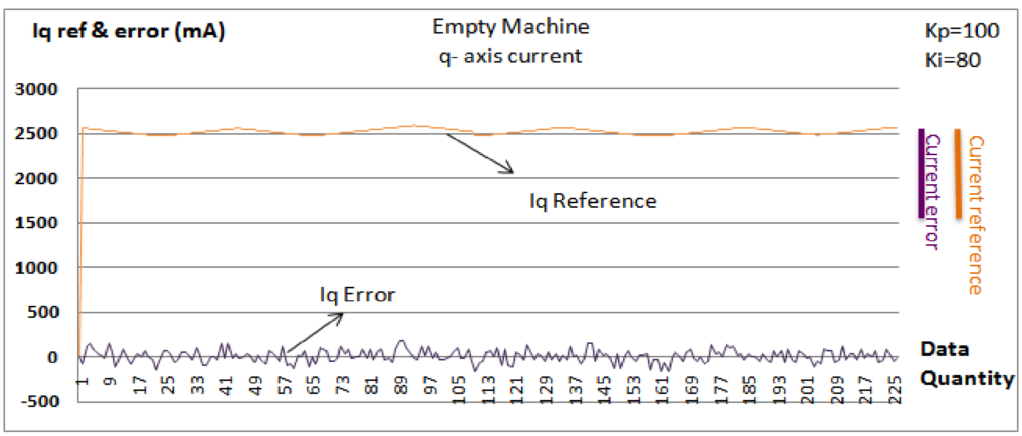


**Figure 52:** $\boldsymbol{I_q}$ reference and error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 100}$ and $\boldsymbol{K_I = 80}$ in spin-dry cycle.

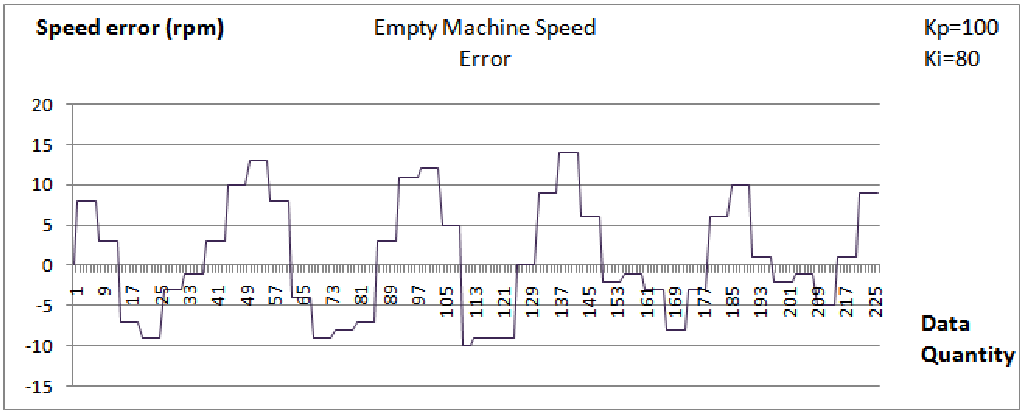


**Figure 53:** Speed error data for loaded washing machine with current PI controller coefficients of $\boldsymbol{K_p = 100}$ and $\boldsymbol{K_I = 80}$ in spin-dry cycle.

When the experimental results are examined it could be seen that the algorithm works as an online PI tuning method even though some counter measures should be taken in order to run it. During the experiments, no critical situations are observed and no operating malfunctions are occured while the PI parameters were being tuned. As a consequence, if the initial simplex is chosen carefully by means of simple empirical methods and the iteration number is limited with a performance index that is chosen with the application constraints in mind, significant improvement on the error of q-axis current could be examined. It is expected that by improving the q-axis error, the system's dynamic performance would also be improved.

As the iteration number increases the algorithm converges to the minimum value unless a dynamic parameter of the system is changed. When a system parameter is changed such as load, as expected, this change directly reflects on the performance index and the tuning algorithm responds to the changes automatically because it is kept running online. It is expected that, this result also will reflect on the dynamic behavior of the system. The next step for utilizing this online tuning algorithm might be the application of the algorithm also in the speed PI control loop to also tune the speed PI.

## 8. SUMMARY AND CONCLUSION

Since automatic washing machines have been introduced to market, they have made a long way in terms of efficiency. Ten years ago it was not possible to use sophisticated algorithms for motor control of washing machines because of the low power of microprocessors and high price. But it is now possible because microcontrollers gradually got cheaper and more powerful over time. With more sophisticated algorithms introduced and applied on washing machines, it gets easier to enhence the efficiency even more.

While the efficiency is getting improved, the customer satisfaction point of view is not neglected. By equipping washing machines with less noisier, long life time efficient motors the manufacturers are aiming to improve the customer satisfaction. These factors make it necessary to switch to PMSM as an actuator for washing machines since they have long life time, have the highest efficiency when controlled with vector control and have better acoustic noise characteristics than other motors used in washing machines such as induction motors, universal motors and BLDC.

However, the washing machine operation is a challenging one due to its speed and torque characteristics. For a motor to meet these characteristics its dynamical response and control should be of high performance segment. With making use of vector control the currents and speed of a PMSM can be controlled with making use of PI type controllers which are convenient. Nevertheless, this operation needs a fine tuning approach that would regulate the PI coefficients over the speed and torque regions of washing operation. Of course this can be done by means of empirical methods after separating the washing operations into different working regions but, this approach is not a feasible one since it is time consuming.

In the scope of this thesis, firstly a general insight is given on the operating regions of a washing operation which can be listed as washing cycle, rinsing cycle, distribution cycle, and spin-dry cycle. The respective speed and torque characteristics for each operation cycle is provided in order to draw a general view of the operation. After providing the operation conditions, a general overview of the motor types used in washing machines along with operating principles advantages and disadvantages is provided and a brief comparison is made between vector controlled induction motors, BLDC and PMSM, which are the best candidates for an efficient washing machine operation.

As a result of this comparison, it is deduced that the best candidate for being an actuator of a washing machine is PMSM considering its characteristics such as, reliability, high torque-volume ratio, low acoustic noise, efficiency etc. Even though the PMSMs are said to be expensive types of motors, the recent increase in copper prices and decrease in rare-earth magnetic materials bring them to an even platform with induction motors and universal motors. If their high efficiency and low noise is taken in to consideration it becomes easier to make a choice between vector controlled induction motors, universal motors, BLDC and PMSM.

In the scope of this thesis, an experimental platform is built on a real washing machine in order to evaluate the performance and prepare the motor control algorithm for mass production. As the study progressed, it has been seen that, if a sensorless vector control algorithm does not have a very fine tuned dynamic control on current controllers the system might malfunction, which is not a desired result in mass production. That is why, the current PI controllers' gains are tabulated over the whole operating region as a first step. The second step taken in order to prevent the system malfunctioning because of poorly tuned PI parameters was to build an online adaptive tuning scheme which automatically tunes the PI parameters as the system's dynamical parameters changes consequting with less time consumed with tuning the PI parameters at the beginning.

In order to build the online adaptive tuning structure the PI parameters are firstly tuned by means of empirical tuning at low speed region with no load. After this tuning operation is done, an optimization algorithm based on Nelder-Mead optimization method is established and several experiments are performed in order to evaluate the performance of the tuning algorithm.

The results of the experiments can be summarized as follows:

- No malfunctioning has occured during the experiments.
- The overall memory consumption of the algorithm did not effect the system performance which is a mandatory feature for applications such as washing machine since the memory of the processor is very limited.

- Significant improvement is examined between the cases of adaptively tuned and empirically tuned systems of which’s results are provided in Chapter 7.
- As expected the algorithm responded to dynamical changes in the system parameters online and with no delay. Moreover, the algorithm managed to tune the PI parameters without causing any malfuntioning on the system after the dynamical characteristics are changed.
- It has been seen that significant improvement can be made by making use of the online tuning algorithm even if it is not used online in mass productions.

With these results, it can be said that the algorithm can be seen as a success specially in development stage. Even though it might not be used in mass production, it can be equipped in the design process in order to find the optimum PI parameters for different working regions approximately.

A further study can be made on the speed controllers of the scheme. Since a washing machine operation is a speed control process, a good response on speed control PI structure is also expected. Within the framework of this study, no such experiment is performed. Because, the tuning of current PI controllers was more curucial than tuning the speed PI controller, since they affect the overall system performance critically.

In conclusion, if one wants to design a high-tech, high-end appliance, which is equipped with a motor whether a washing machine or an air conditioner, one would see that the state-of-art on the appliance industry is on vector control of PMSM. The appliance industry is trying to catch up with the new energy regulations and the trend in green appliances which causes a raise in the demand of using sophisticated motor control algorithms such as vector control and equipment of efficient motor structures such as PMSM. In a couple of years, if one wants to buy an appliance, he most probably will buy one with a vector controlled PMSM.

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