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Simulation and analysis of Switched Reluctance Generator for renewable energy applications

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A tutti coloro che mi hanno accompagnato in questo viaggio

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List of Symbols

AC	alternating current	
DC	direct current	
emf	Electromagnetic force	
LSRM	Linear Switched Reluctance Motor	
OWCs	Oscillating water column	
SR	Switched Reluctance	
SR machine	Switched Reluctance machine	
SRG	Switched Reluctance Generator	
SRM	Switched Reluctance Motor	
SW	Switching	
ER	Energy Ratio	
B	Friction	[Nms]
C	Capacitance	[F]
e	Back-emf	[V]
f	frequency	[Hz]
i	current	[A]
i_g	current to the grid	[A]
I_{MAX}	maximum current	[A]
i_{ph}	phase current	[A]
I_{in}	input current	[A]
I_{out}	output current	[A]
I_0	net generated current	[A]
i_k	k value of the current	[A]
$\vec{\imath^*}$	coniugate current phasor	
J	Inertia	[Nms]
L	inductance	[H]

L_a	aligned inductance	[H]
L_{a_s}	saturated aligned inductance	[H]
L_{max}	maximum inductance	[H]
L_{min}	minimum inductance	[H]
L_u	unaligned inductance	[H]
m	number of phases	
N_r	number of rotor poles	
N_s	number of stator poles	
P	active power	[W]
p_a	air gap power	[W]
p_i	instantaneous input power	[W]
P_{gen}	generated power	[W]
P_m	Mechanical power	[W]
P_{out}	Output power	[W]
Q	reactive power	[VAR]
q_{dwell}	conduction angle	
R	Energy stored not converted	[J]
R_s	Phase resistance	[Ω]
R_{stator}	Stator resistance	[Ω]
t	Time	[sec]
T_{em}	Electromagnetic torque	[Nm]
TL	Torque load	[Nm]
T_f	Friction torque	[Nm]
v	Phase voltage	[V]
V_{DC}	Source voltage	[V]
V_g	Grid voltage	[V]
V_i	Inverter voltage	[V]
$\vec{V_i}$	Inverter voltage phasor	

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$V_{ph\ to\ ph}$	Phase to phase voltage	[V]
w	pulsation	[rad/s]
W_e	Absorbed energy	[J]
W_f	Stored energy	[J]
W_m	Mechanical work	[J]
W'	Magnetic coenergy	[J]
X	Line impedance	[Ω]
α_s	stator pole arc	[rad or deg]
α_r	rotor pole arc	[rad or deg]
δ	Inverter voltage phase	[rad or deg]
ε	step angle	[rad or deg]
ε_p	Excitation penalty	
θ	Rotor Position	[rad or deg]
ϑ_0	Initial position	[rad or deg]
θ_{1d}	Angle at which pole overlaps ends	[rad or deg]
θ_a	aligned position	[rad or deg]
θ_{ext}	Angle at which the flux reaches zero	[rad or deg]
θ_k	k value of the rotor position	[rad or deg]
θ_{on}	turn-on angle	[rad or deg]
θ_{off}	turn-off angle	[rad or deg]
θ_u	unaligned position	[rad or deg]
λ	Flux-linkage per phase	[Vs]
Φ	Current phase	[rad or deg]
Ψ	Flux-linkage	[Vs]
Ψ_k	k value of the flux-linkage	[Vs]
Ψ_{MAX}	maximum flux-linkage	[Vs]
ω	rotor speed	[rad/sec or rpm]
ω_0	Initial speed	[rad/sec or rpm]

Riassunto Esteso

Sommario- Lo scopo della tesi è lo studio di un Generatore Switched Reluctance per future applicazioni nel campo delle energie rinnovabili, nello specifico della generazione di energia dal moto ondoso. In particolare viene simulato un modello del generatore con MATLAB® SIMULINK® connesso ad una rete in modo da estrarre la massima potenza possibile.

Introduzione

La macchina Switched Reluctance è una macchina elettrica in cui la coppia è prodotta dalla tendenza della sua parte mobile di muoversi nella posizione di riluttanza minima, ossia di massima induttanza. E' un tipo di macchina sincrona con avvolgimenti di statore e senza avvolgimenti o magneti di rotore in cui sia statore che rotore sono a poli salienti. Gli avvolgimenti di statore su poli diametralmente opposti sono connessi in serie o parallelo per formare una fase della macchina. Ci sono varie combinazioni di poli di statore/rotore come 6/4 (6 poli di statore e 4 di rotore) , 8/6 , 10/8 ecc. ma in questa tesi l'analisi è fatta su un SRG 6/4. Si può inoltre eseguire una classificazione delle varie tipologie di macchina dividendole in lineari o rotanti (come nel caso in questione) e a campo radiale o assiale. I motivi del perché possa essere conveniente l'impiego di questa macchina possono essere riassunti nei seguenti punti:

- meno materiale viene impiegato essendo gli avvolgimenti solo sul lato statore e non essendo presenti ne avvolgimenti ne magneti sul lato rotore, implicando quindi una notevole riduzione del costo;
- A medio alte velocità offre una densità di potenza equivalente o superiore al motore a magneti permanenti;
- Essendo le fasi indipendenti, il guasto di una fase non ha effetti sulle altre e in particolari condizioni la macchina può continuare ad operare.

Con il controllo in corrente questa macchina ha trovato impiego in applicazioni a bassa velocità come generatori eolici o appunto generatori da moto ondoso. Tecnologie esistenti che potranno vedere una possibile applicazione con un SRG sono gli assorbitori puntiformi a singolo o doppio captatore solitamente usati con motori lineari, o l' Archimede Wave Swing (AWS) e infine ,più utilizzati con motori rotanti, a colonna d'acqua oscillante.

Principio di funzionamento del motore Switched Reluctance

Consideriamo un 6/4 SRM rotante e consideriamo che I poli di statore della prima fase siano allineati con I poli di rotore come mostrato in figura. Sia applicata una corrente nella prima fase. Un flusso si stabilisce tra i poli di statore della prima fase e i poli di rotore. Una volta allineati la corrente di statore viene spenta ed decresce fino a zero mentre la corrente nella seconda fase viene attivata, spingendo il rotore nella direzione (in rosso) opposta al verso di alimentazione delle fasi (in blu) come mostrato in figura. Una volta allineati i poli si passa all'alimentazione della terza fase e cosi via.
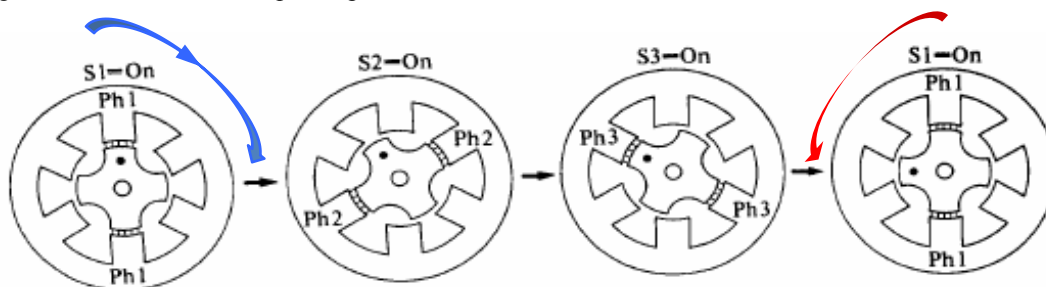
Figura 1 Ciclo completo di eccitazione delle fasi in un 6/4 SRM

La produzione della coppia può essere spiegata con il principio della conversione di energia elettromeccanica. Come detto durante l'alimentazione di una fase la coppia tende a spostare il rotore verso la posizione di riluttanza minima causando quindi un aumento dell'induttanza di fase. Quindi una coppia positiva è ottenibile alimentando la fase durante l'aumento dell'induttanza.
Si ha :

$$T_{em} = \left[\frac{dW'}{d\theta} \right]_{i=const}$$

Dove T_{em} è la coppia elettromagnetica e W' la co-energia magnetica e si considera quindi la sua derivata rispetto all'angolo θ. In condizioni lineari diventa:

$$T_{em} = \frac{1}{2}i^2 \ \frac{dL}{d\theta}$$

Espressione della coppia in queste particolari condizioni che rispecchiano quelle utilizzate nella tesi.
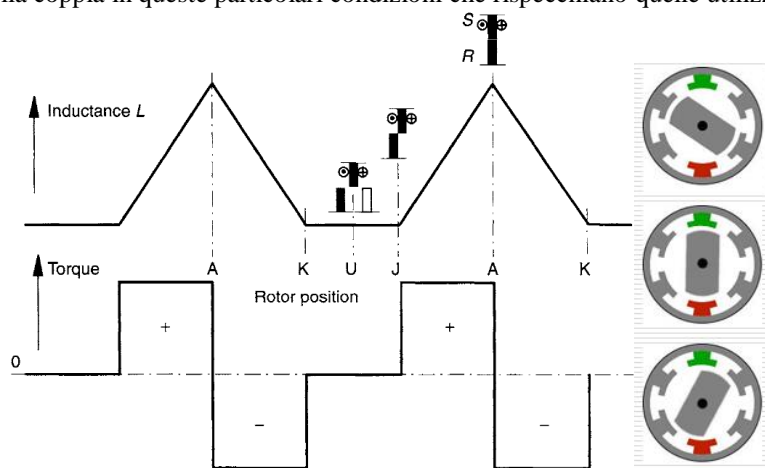
Figura 2: Variazione dell'induttanza e della coppia con la posizione di rotore; la corrente negli avvolgimenti è assunta costante

Essendo la coppia indipendente dalla polarità della corrente, il convertitore utilizzato per l'alimentazione delle fasi è del tipo a ponte asimmetrico come mostrato in figura, dove viene riportata solo una fase essendo le altre equivalenti.
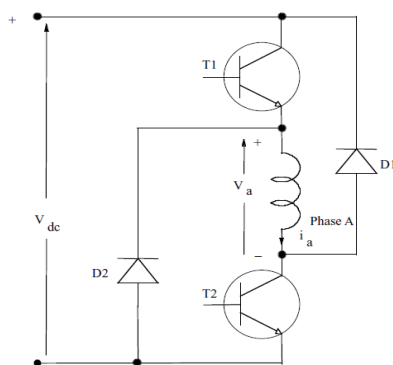
Figura 3: singola fase del convertitore

Il comando per l'alimentazione delle fasi altro non è che un controllore ad isteresi dove chiudendo i transistor T1 e T2 la fase A viene alimentata dall'alimentatore Vdc permettendo alla corrente di

raggiungere il valore di riferimento. Quando questo viene superato di un certo valore predefinito i transistor vengono aperti e la corrente si richiude sui diodi permettendo la sua diminuzione fino al raggiungimento del valore minimo dal quale verranno riattivati i transistor , questo fino al termine del ciclo di alimentazione di quella fase.

Switched Reluctance Generator

La macchina Switched Reluctance può operare come generatore cambiando gli angoli di alimentazione . Nel funzionamento da generatore gli angoli sono scelti in odo che la corrente percorra gli avvolgimenti quando l'induttanza è decrescente ossia $\frac{dL}{d\theta} < 0$. Quando $dL/d\theta < 0$ la forza contro-elettromotrice è negativa e tende ad aumentare il valore della corrente e convertire la Potenza meccanica in elettrica. In figura è mostrato il circuito di una fase da generatore e si vede come sia il convertitore che il carico sono collegati allo stesso D.C. bus.
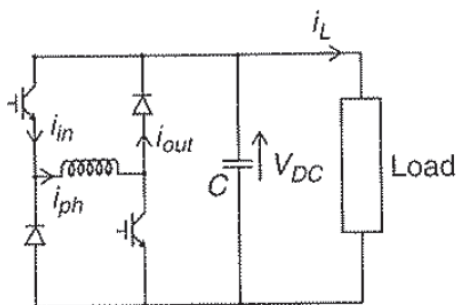
Figura 5: Circuito di una singola fase nel funzionamento da generatore

Da θ_{on} a θ_{off} l'alimentatore fornisce la Potenza necessaria attraverso il convertitore alla macchina che viene poi immagazzinata come energia magnetica. Quando gli interruttori vengono spenti la corrente generata circola attraverso i diodi ricaricando l'alimentatore. Se la potenza generata è maggiore della potenza di alimentazione allora il sistema ha generato potenza netta convertendo potenza meccanica in elettrica. La potenza generata verrà consegnata in rete quindi il sistema necessiterà di un inverter DC/AC.

Implementazione modello SRG

In figura 6 è mostrato il layout generale del modello dell'SRG senza la parte di connessione mostrata dopo poiché implementata all'interno del blocco del convertitore per motivi di spazio. Il modello può essere diviso in 4 parti principali: l'alimentazione esterna, il convertitore, il generatore, il sensore di posizione. Le simulazioni e analisi sono condotte assumendo una potenza, velocità e coppia costanti in condizioni stazionarie già a regime. La coppia meccanica in input TL produce una velocità angolare essendo

$$P_m = TL\,\omega$$

Il secondo input è la corrente necessaria per produrre il campo magnetico; questa è inizialmente fornita da un'alimentazione esterna che verrà poi disconnessa quando il banco di condensatori sarà carico e quindi potrà sostituirsi lui stesso all'alimentazione.
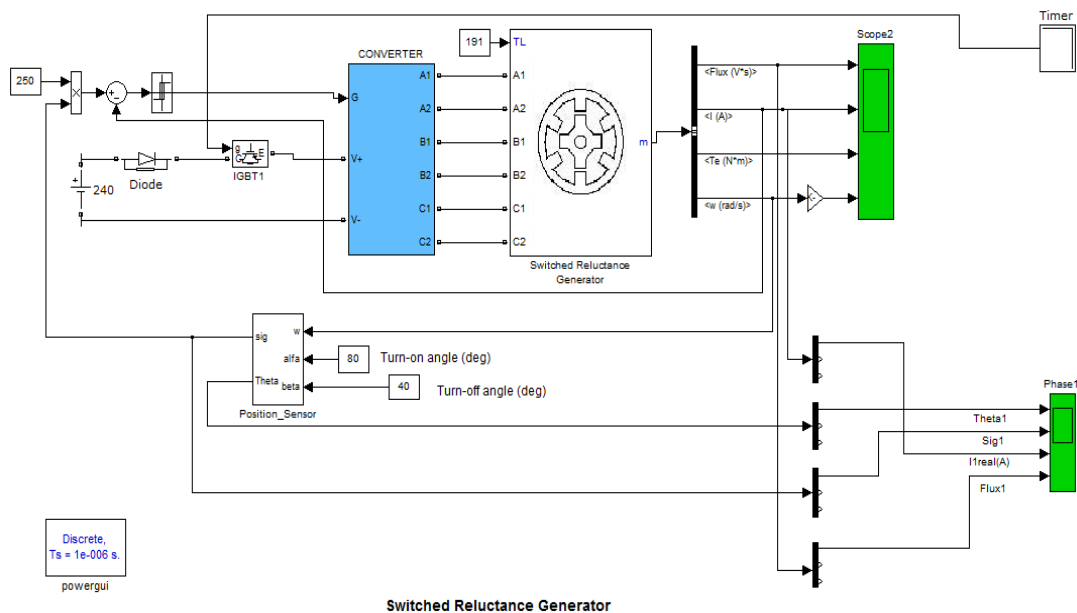
Figure 6 : SRG layout generale

Fissando gli angoli di accensione e spegnimento durante la pendenza negativa di $dL/d\theta$ il sensore di posizione fornisce gli impulsi per il controllo di ogni fase. L'angolo fissato è lo stesso per tutte e tre le fasi ma con un blocco integratore interno vengono fissate le condizioni iniziali delle tre fasi in modo da poter utilizzare lo stesso blocco. Essendo la macchina un modello 6/4 con tre fasi , le condizioni iniziali saranno $0°, -30°, -60°$. Il polo di rotore rispetto la prima fase è allineato a inizio simulazione mentre rispetto alla seconda e terza fase sono sfasati di -30 e -60 gradi. L'angolo può cambiare da 0 a 90 , e quando il contatore raggiunge il valore massimo viene fatto ripartire da 0. L'output del sensore di posizione andrà quindi a diventare il comando di corrente per le varie fasi. Tramite un controllore ad isteresi la corrente viene mantenuta al livello di riferimento nelle varie fasi al giusto momento. Il convertitore è quindi collegato alla macchina e al banco di condensatori che viene caricato durante l'apertura dei transistor dei vari rami di fase. Il banco di condensatori è collegato a un inverter DC/AC per l'immissione di potenza in rete , che è quindi poi simulata utilizzando dei parametri piuttosto reali. La tensione di rete dovrà avere un valore leggermente inferiore della tensione del banco di capacitori in modo da avere la giusta direzione. L'obiettivo è andare a estrarre la massima potenza disponibile mantenendo la tensione sul condensatore a 240 [V] necessari per l'alimentazione della macchina. Quando la tensione sul condensatore è maggiore del valore di riferimento significa che più potenza può essere estratta viceversa se è minore del valore di riferimento allora dovrò ridurre la potenza immessa in rete. La configurazione di controllo adottata in questa tesi è basata sulla generazione di un'onda sinusoidale bilanciata in cui l'indice di modulazione dell'ampiezza m e l'angolo di sfasamento con la corrente δ sono controllati tramite due controllori proporzionali integrati PI. L'indice di modulazione segue la tensione del condensatore V_{DC} in diversi modi: se V_{DC} aumenta significa che più Potenza può essere estratta e quindi anche l'ampiezza della corrente di rete aumenterà. Un modo per permettere alla corrente di crescere è aumentare la caduta di tensione sull'induttanza di rete che può essere fatta aumentando la tensione dell'inverter attraverso un aumento dell'indice di modulazione m. D'altra parte, per la correzione del fattore di potenza, deve essere controllato in modo da portare il vettore di corrente parallelo alla tensione di rete per avere fase nulla in modo da ottenere la massima potenza attiva e mantenere a zero la potenza reattiva quindi un'equivalente spostamento di angolo δ deve essere fatto.

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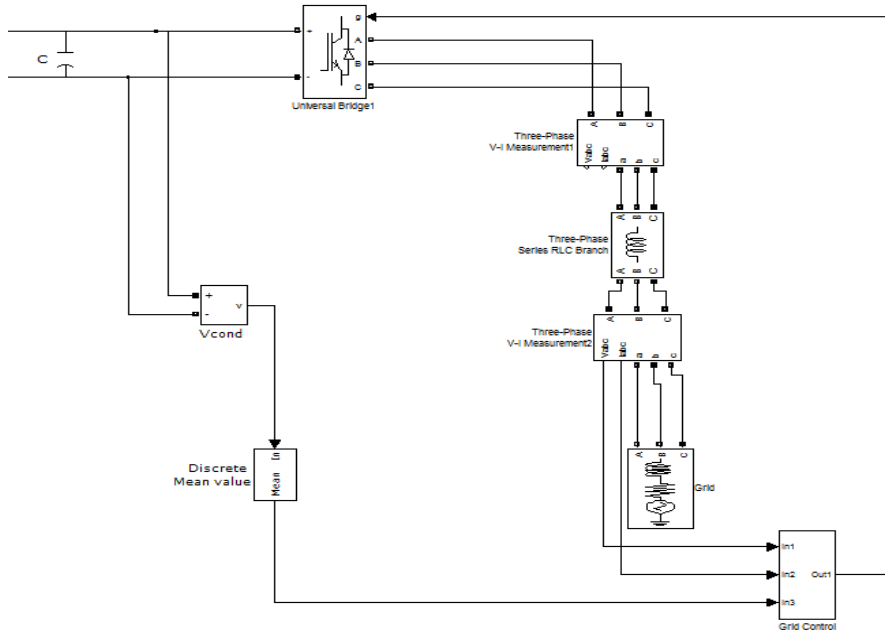
Figura 7: lato connessione rete

Risultati

I risultati ottenuti e presentati sono in riferimento ad una macchina 6/4 , 60 [kW] in condizioni di linearità e in condizioni stazionarie con una velocità costante pari a 3000 giri/minuto essendo questa la velocità nominale della macchina attuando così un controllo di corrente.
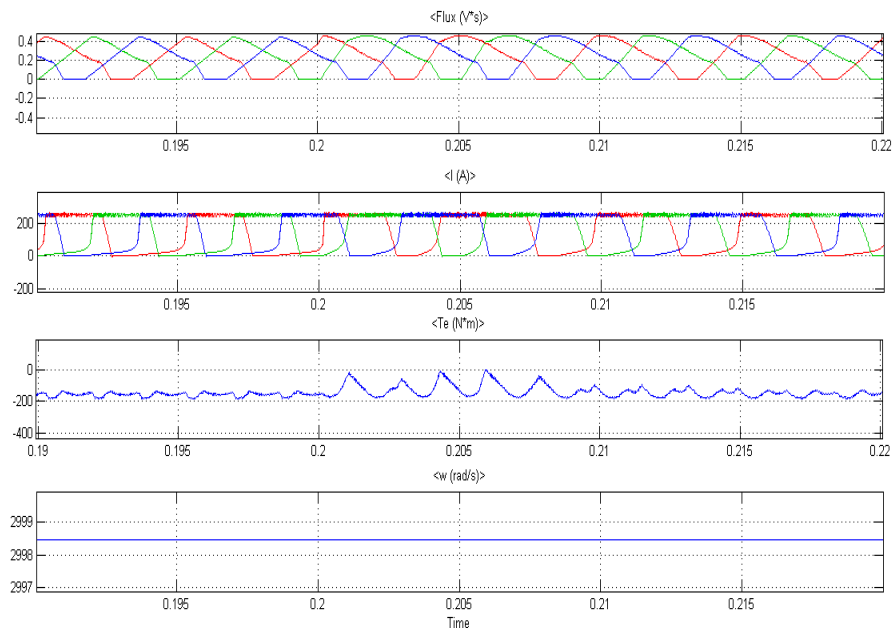
Figura 8 : Forme d'onda risultanti

Vi sono dei punti instabili come si può notare dal grafico a 0.02s dovuti alla disconnessione dell'alimentazione esterna e al collegamento del condensatore, ora carico, come nuova sorgente di alimentazione in grado di caricarsi e scaricarsi quindi la macchina diventa ora autosostenuta. Una seconda leggera instabilità si ha al collegamento del controllo di rete. Questo perché il controllo prevede un mantenimento della potenza reattiva a zero ma essendo inizialmente un ciclo aperto, poiché la macchina non ancora in grado di autosostenersi, le grandezze hanno fasi diverse da quelle mantenute dal controllo e quindi necessitano di tempo per arrivare al valore desiderato. Da figura 15 si può notare il mantenimento della tensione sul condensatore al valore desiderato per l'alimentazione oscillando tra $240 \mp 40 \ [V]$ per quanto spiegato in precedenza sul prelievo di potenza.
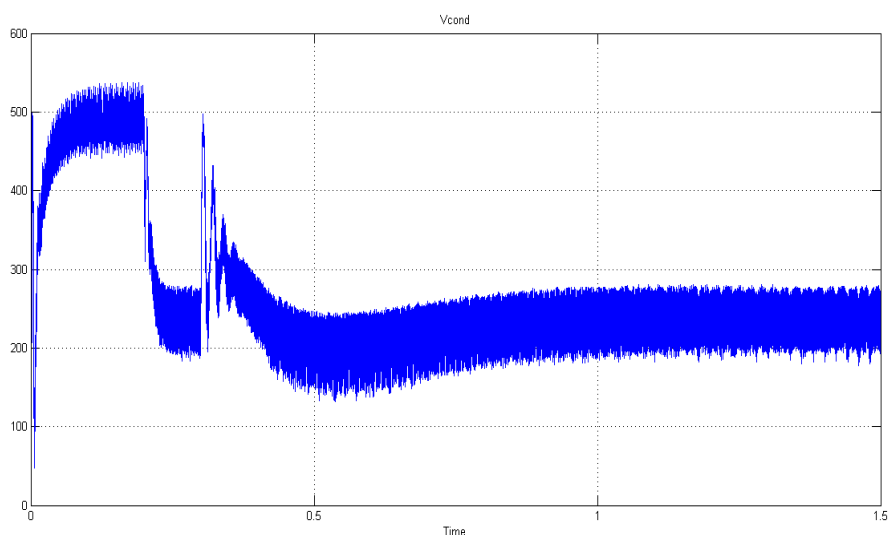
Figura 9: profilo di tensione del condensatore

Infine figura 10 mostra i profili di Potenza attiva e reattiva diretta in rete.
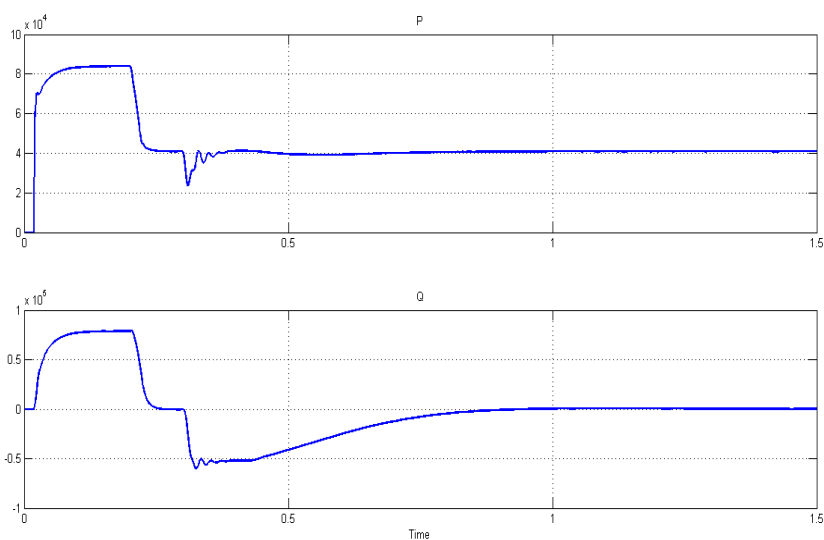
Figura 10: profili di Potenza attiva e reattiva alla rete

Dopo un periodo iniziale durante il quale si ha la carica del capacitore, la potenza attiva è mantenuta ad un valore circa costante di 41 [kW] mentre la potenza reattiva viene mantenuta a zero dal controllo.

Considerazioni

Messo a punto il modello dello SRG che può adottare differenti strategie di controllo, è stato possibile trovare una condizione di ottimo per una velocità costante in modo da produrre la massima quantità di Potenza attiva da immettere in rete. Le condizioni trovate sono per una macchina 6/4 , 60[kW] alimentata a 240 [V] e una corrente di riferimento di 250 [A] con una velocità costante pari a 3000 giri/min sono angoli di attivazione e spegnimento pari a $\theta_{on} = -30°$ e $\theta_{off} = 40°$ [4] [5] con una produzione di potenza attiva immessa in rete pari a $P = 41 [kW]$ e una potenza reattiva Q mantenuta a zero.

L'analisi eseguita è solo l'inizio dell'obiettivo finale che è lo studio dell'applicabilità della macchina all'energia del moto ondoso. Questo comporta lo studio del profilo di coppia generato dalle onde del mare ed essendo questo variabile anche la velocità sarà variabile quindi un controllo sugli angoli di attivazione deve essere implementato seguendo quello che potrebbe essere la tecnica utilizzata nei pannelli fotovoltaici dell'MPPT (Maximum Power Point Track).

Questo ha previsto il reinserimento del blocco meccanico per utilizzare input di coppia variabili, tuttavia i risultati non sono discussi in questa tesi. Altre caratteristiche della macchina dovranno essere analizzate come il funzionamento di questa in condizioni di guasto di una fase , l'analisi delle perdite magnetiche e lo studio della stessa con differente numero di poli in modo da diminuire il ripple di coppia, motivo del quale esistono ancora forti dubbi sul possibile utilizzo della macchina. Lo studio dell'utilizzo di questa macchina nel campo del moto ondoso può essere un'interessante alternativa pulita ed economica di produrre energia.

Abstract

The objectives of the investigation is to study a SRG (Switched Reluctance Generator) for future wave energy applications. In particular is intended to design and simulate a SRG model with MATLAB® SIMULINK® discovering the characteristic of the machine, the profile of current, torque ecc , figure out the best strategy in order to produce the large amount of power.

The machine is later connected to a grid converter in order to evaluate how much energy is possible to extract with this type of machine. A control on the grid side is also implemented to maintain the current in phase with the grid voltage. This work started from a demo of a Switched Reluctance Motor already implemented in the library of Simulink in SimPowerSystem that has been modify to convert the SRM in SRG. The grid side and control of reactive power started from a previous model already developed in the frame of the HVDC project. The model then is adapted to the requirements of the machine operations.

In the introduction is presented the general characteristics of a SR machine (Switched Reluctance machine), including the different possible configurations and the possible applications in the wave energy describing the technology and its advantages and disadvantages. In the second chapter advantages and disadvantages of the machine are presented and consideration on the torque production and characteristics are discussed with the machine operating as a motor in order to allow the reader to understand the changes apllied to the machine for the function as a generator, which is discuss in the chapter 3. So after a better explanation of the principle of the machine in the second chapter, the 3rd chapter discuss about SR machine as a generator, so the differences are described and a general concept of circuit is explained. The 4th chapter shows the model of the generator done with Simulink describing every part of the electric circuit. At the end results and graphics are described and explained figuring out the conclusions and the future work that will be done.

The purpose of this thesis is investigate and analyze the SRmachine and its applicability in the generation of electric energy from wave energy that is not usual for the limitation that it presents and that will be discussed later. As explained in the 1st chapter this machine has a lot of advantages compare to other type of electric machine and this is why is interesting study the possibility of its implementation instead of other type like PM machine (Permanent Magnet) etc. In wave energy applications.

1 Introduction

1.1 Switched reluctance technology

The SRM is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized (or the reluctance is minimized).

SRM is a type of synchronous machine that has wound field coils of a DC motor for its stator windings and has no coils or magnets on the rotor. Both the stator and rotor have salient poles so the machine is a doubly salient, singly excited machine.

Stator windings on diametrically opposite poles are connected in series or parallel to form one phase of the motor. There are several combinations of stator and rotor poles , such as 6/4 (6 stator poles and 4 rotor poles) , 8/6 , 10/8 etc. and the configuration of higher number of stator/rotor pole combinations has generally less torque ripple.
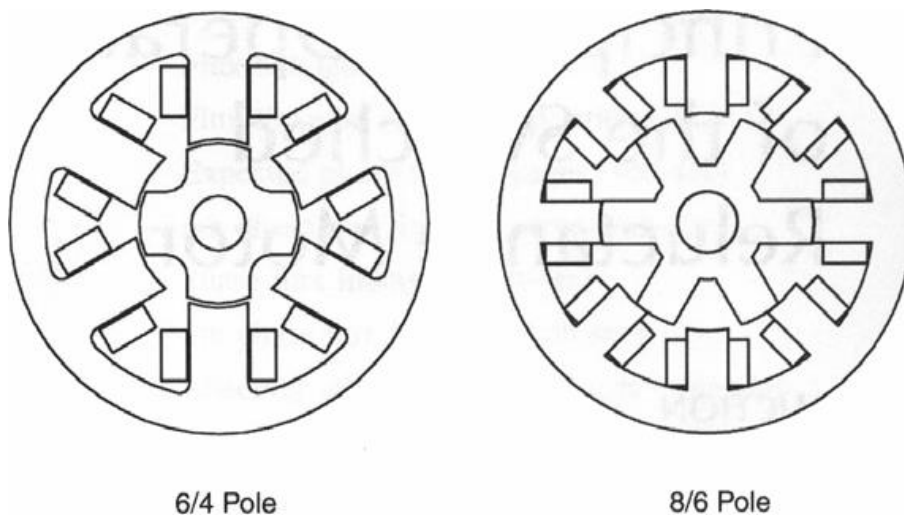
6/4 Pole   8/6 Pole

Figure 1.1: A 6/4 pole and 8/6 pole SRM

1.1.1 Configuration

First of all an initial classification is made on the nature of the motion that can be rotating or linear.

The linear SRMs (LSRMs) have found application in the marketplace by catering to machine tool servos.

The rotary machine-based SRM is differentiated to radial field SRM and axial field SRM by the nature of the magnetic field path as to its direction with respect to the axial length of the machine.
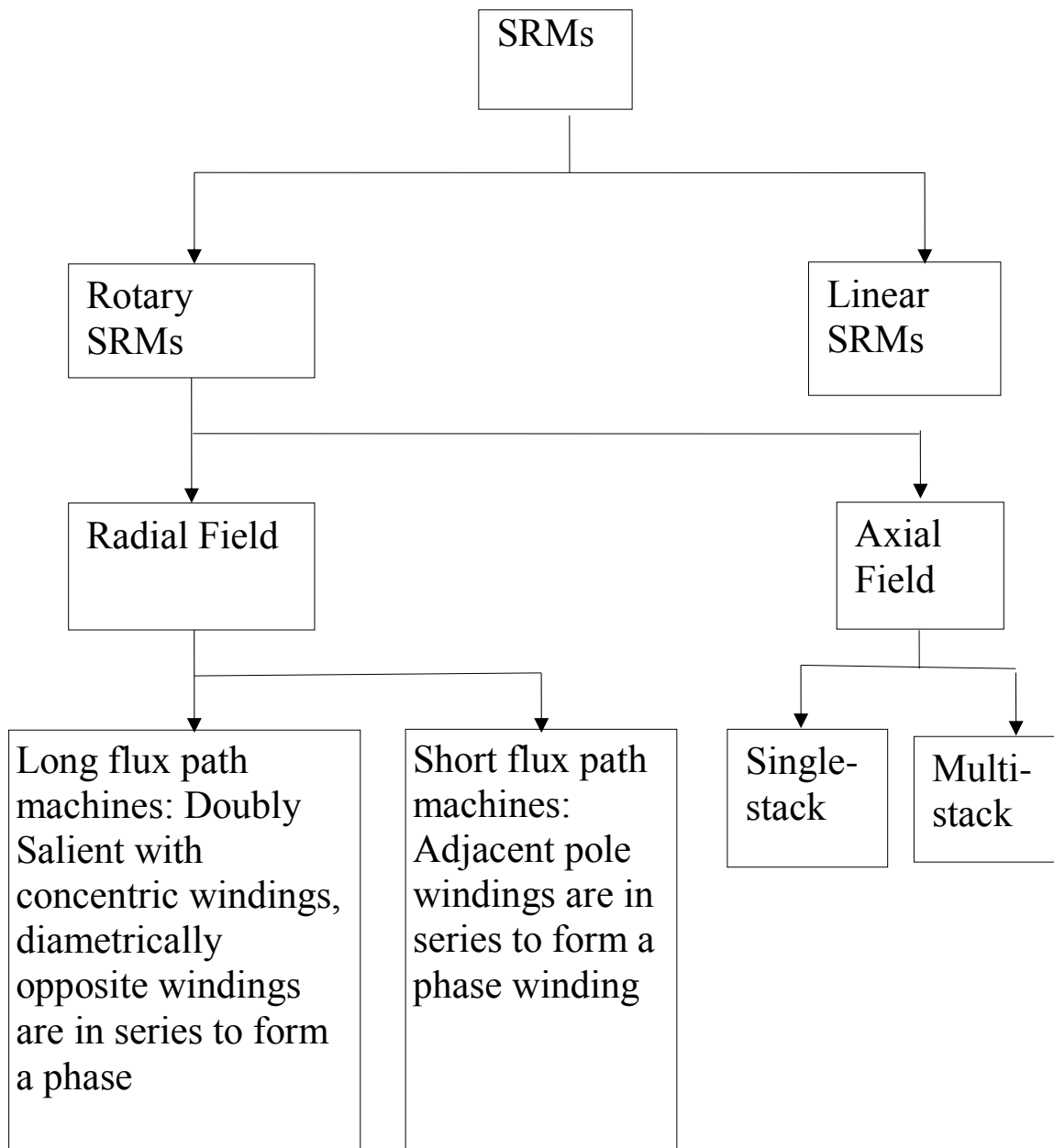
Figure 1.2: Classification of the type of SRM

1.1.2 Rotary SRM

In the radial field SRM the magnetic field path is perpendicular to the shaft or along the radius of the cylindrical stator and rotor as we can see in figure 1.3, while in the axial field SRM the magnetic field path is along the axial direction as shown in figure 1.4.
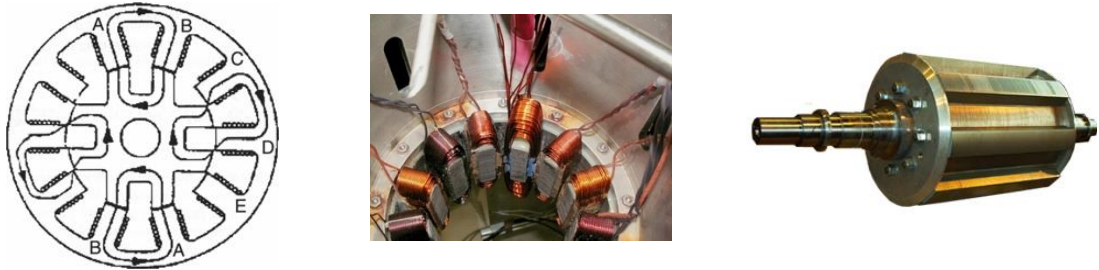
Figure 1.3: Radial field SRM.
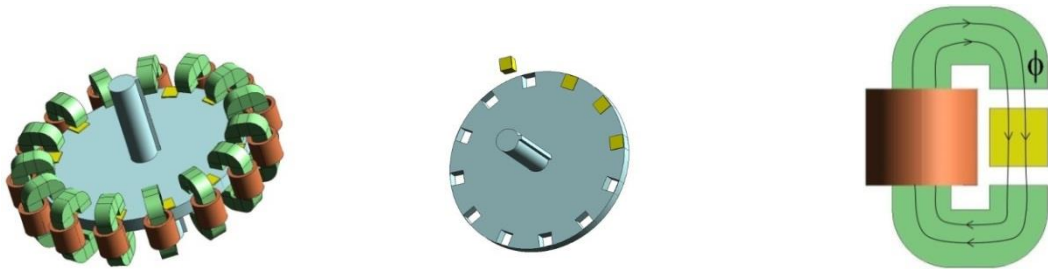
Figure 1.4 : Axial field SRM.

1.1.3 LSRM (Linear Switched Reluctance Motor)

In this type of machine the motion of the motor is linear. A LSRM may have windings either on the stator or translator (the moving part). Fixed part is called track while the moving part is called translator.Compared to its single-sided counterpart, a double-sided LSRM (DLSRM) has a more propulsion force to mass ratio and normal force can be counteracted from serially connected excitation windings and a symmetric machine structure.
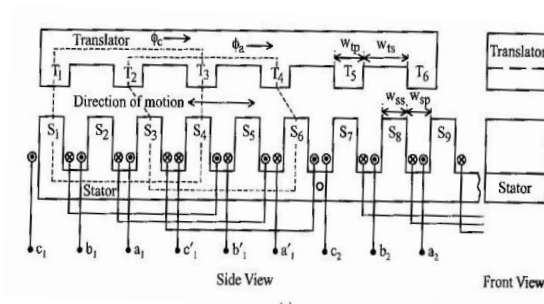
Figure 1.5: One side LSRM winding on the translator
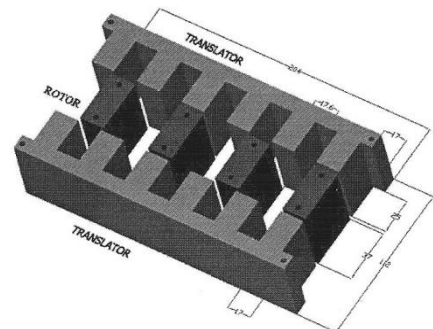
Figure 1.6: Two sided LSRM with

1.2 Features of Switched Reluctance Machine

In this chapter is explained the advantages that will obtain with the use of a Switched reluctance machine taken from [2].

1.2.1   MACHINE

Advantages

• Less materials is needed cause windings are on the stator only, without windings or magnets on the rotor so in term of cost is also more convenient;

• For the fact that windings are concentric around a pole and not distributed like ac or dc machines means a greater manufacturing economy;

• The inactive part of the materials are minimize for the fact that concentric windings reduce the end-turn buildup and this mean a lower resistance and copper losses compared to the distributed winding of other machines.

• The rotor is the smallest of any machine and has the lowest moment of inertia, thus giving a large acceleration rate for the motor;

• It is a brushless machine and therefore is superior from a maintenance point of view compared to dc machines;

•It is mechanically robust and therefore naturally suited for high-speed operation because the rotor doesn't have windings or magnets

• The higher heat is produced on the stator so cooling results easier for the accessibility of the stator compared to the rotor. The rotor losses are much smaller compared to the stator, unlike the case for dc and induction machines. Permanent magnet synchronous and brushless dc machines would be comparable in this respect.

• Skewing is not required to decrease cogging torque or crawling torque, as it is for induction and permanent magnet synchronous and brushless dc machines. This machine does not produce cogging or crawling torques.

•The power density is quite similar and sometimes also higher than for induction machines but lower than permanent magnet synchronous and brushless dc machines. However this thing is true only for low speeds (i.e., below 20,000 rpm); for higher speeds, the switched reluctance motor offers equivalent or higher power density. This has to remember when will speak about the possible applications in wave energy of the machine;

•Because of the electrical separation between the windings from each other and the mutual coupling induction is negligible, generally the fault of one phase has no effect on other phases. This advantage is present only in Switched Reluctance Machine. For some permanent magnet brushless dc machines, such a concentric winding with one slot pitch is being introduced and may bestow some of the benefits of the SRM.

• The absence of current in the winding produce no induced emf in the SRM, because this one is a function of the current and a phase winding fault cannot be sustained if the input current is cut off. Such is not the case for induction or permanent magnet synchronous and brushless dc machines. This leads to higher reliability in an SRM compared to any other electrical machine.

• The freedom to choose any number of phases is inherent in the SRM and lends itself to high reliability if one or more phases fails during operation. Has to remember that all the phases are electrically independent.

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• The machine is an inherent position transducer, as its inductance is uniquely dependent on rotor position and excitation current. During the inactive period of each phase winding, the rotor position can be extracted by measuring the inductance. Such a feature is difficult to exploit with induction and permanent magnet synchronous machines as there is no inactive period for the windings. The rotor position information is extracted in these machines in other ways, but all of the methods are fraught with complexities in implementation and signal processing. Extraction of discrete rotor position information is possible with a permanent magnet brushless dc machine because there is an inactive period for each winding in this machine, but a direct relationship between rotor position and a measurable quantity such as inductance is not available with the brushless dc machine as it is in the case of the SRM.

Disadvantages

• Torque ripple is high but can be reduced by controlling the overlapping phase currents.

• Acoustic noise is high, but its causes are being studied and some recommendations have resulted in considerable noise reduction compared to the first-generation machines. This will be interesting when it will speak about applications under sea.

• Because of the salient rotor , friction and wind losses are high at high speeds. They can be reduced by smoothing the rotor surface by filling in the rotor interpolar space with inert material.

• The SRM requires an electronic power converter to run and doesn't have line-start capability; therefore, it is difficult to compete in an application requiring this aspect, where an induction motor is an asset. Permanent magnet synchronous and brushless dc machines have the same disadvantages of the SRM in this regard.

•The information about the position is necessary for the SRM control, but also for permanent magnet synchronous and brushless dc machines; the only exceptions are for induction and dc machines. To compete for applications requiring no position sensor and absolutely low cost, the SRM must incorporate sensorless position control. Induction and dc machines are superior in this regard, at least for low-performance applications.

• Radial forces are high at aligned positions and minimum at unaligned positions; variation over half the rotor pole pitch can contribute to faster wear and tear of the bearings if there are rotor eccentricities and uneven air gap, which is the major source of noise in SRMs. Such a phenomenon is not present in other machines.

1.2.2   CONVERTER

Advantages

• The SRM requires only unidirectional current for its four-quadrant operation and there are many power converter topologies with less than two switches per phase that can be used to operate the SRM. This is also translate in less cost for the converter cause is simpler and less power switching loss for the smaller number of switches.

• Because the power switches are always in series with the phase winding and together they are in parallel to the dc source voltage, at no time could a shoot-through fault occur, as in the case of the six-switch H-bridge inverters. This assures high reliability for this converter compared to other converters.

• Failure of one switch in a converter phase need not interrupt operation of the remaining phase legs of the converter and hence the SRM drive system operation. That is not the case with the ac motor drives under the same circumstance.

• Because the number of power switches can be reduced in the SRM drive, a considerable saving can accrue from a reduction in the number of logic power supplies and gate drivers and reduced heatsink area and volume, resulting in great reduction in the converter packaging and enclosure size. In high-volume applications, this could lead to considerable savings of transportation costs and overall material and manufacturing labor costs.
Such a distinct advantage is generally not available for other ac drives.

Disadvantages

• A separate freewheeling diode for each switch is necessary in all SRM converter topologies, which cannot use anti-parallel diodes in the switches, as in the case of the H-bridge inverters. This may increase the cost if two switches per phase converter are employed for an SRM in comparison to other inverter-driven machines. This may be mitigated by reducing the number of switches and also by a special converter module developed for high-volume applications so that the overall converter cost can be reduced.

1.3 Low speed wave energy application

There are not many literature about low and medium speed operation for a SRG. The current chopping mode control method is normally used at low speed for the wind energy conversion system (WECS) application [14] .
The WECS application ensures an optimum operation of the wind turbine for a particular wind speed by relying on the conversion coefficient of the turbine, but this method requires measurement of wind speed . A power control strategy was used to maintain the required load demand. Another method to control the output power is a controller to regulate the turn on angle whilst the turn off angle is kept constant [15]. The resources on the application of the machine for the control strategies in wind energy are still limited. To keep constant the output power the machine has to follow a set of reference value power and this fact limit the potential of the machine to convert energy.
Based on this the application of this machine to the wave energy will be interesting, also cause often a wind turbine is required.
Ocean waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves is considerable, but is relatively immature compared to other renewable energy technologies [6]. This renewable energy is characterized by the fact that , like wind energy and solar energy, is an intermittent source of energy. This mean that it is not able to product continue and constant energy but is characterized by irregular and unpredictable profile. In figure 5.1 is possible to see the difference between intermittent and not energy.
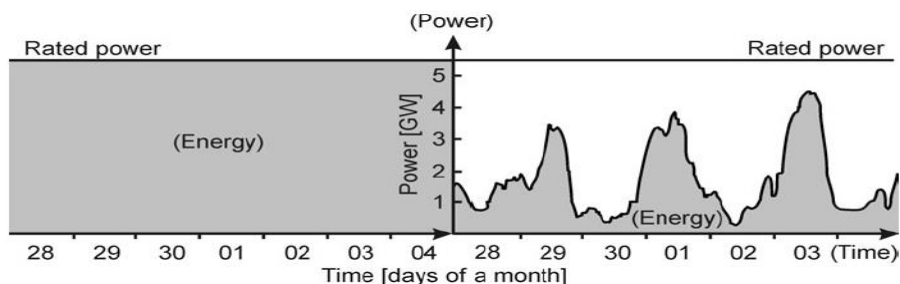

Figure 1.7: The difference between an intermittent and a non-intermittent energy source of equal rated power.

The advantages of non-intermittent energy is that they are able to product every time energy at the rated power. This is good for the economy of the plant cause is exploited always at the maximum or a high power. For the intermittent energy source is different; the cost of the plant is determined by the rated power (the maximum power that can be extract) so is not connected to the effectiveness energy product. So the nominal power shouldn't fixed too high cause the cost will be high and the production of the power will never be like that cause the natural resource are limited and intermittent.

Benefits of wave energy

Using waves as a source of renewable energy has more advantages compared to the other type of generating energy.
In particular :

a) Sea waves offer the highest energy density among renewable energy sources [**7**];

b) Limited negative environmental impact in use;

c) Natural seasonal variability of wave energy, which follows the electricity demand in temperate climates [7];

d) Waves can travel large distances with little energy loss. Storms on the western side of the Atlantic Ocean will travel to the western coast of Europe ,supported by prevailing westerly winds;

e) wave power devices can generate power up to 90 per cent of the time, compared to ~20–30 per cent for wind and solar power devices [8] [9].

1.4 Wave energy conversion

The devices for the energy conversion from the wave energy are called *wave energy converters* and they can be classified in different way: from their position, type and from their modes of operation.

1.4.1 Classification from the position

The energy carried from the waves can be influenced from different factors like the distance from the shore; one first classifications of WECs (Wave Energy Converters) is:

a) *shoreline devices ;*

b) *nearshore devices ;*

c) *offshore devices.*

Shoreline devices

The advantages of shoreline is that they are close to the utility network so they can be moored on the seabed where the water is not deep or fixed to the rocks on the shore. They are easy to maintain , the access to them is every time possible and this mean a reduction of installation costs. As waves are attenuated as they travel through shallow water they have a reduced likelihood of being damaged in extreme conditions. Other advantages are that don't need deep moorings and neither long cables for the transport of the energy. However the biggest disadvantage is the quantity of energy from the wave that generally is lower near the shore.; this can be partially compensated by natural energy concentrated locations, called hot spots.

Nearshore devices

Nearshore devices are defined as devices that are in relatively shallow water ($\sim 10 \div 20$ meters) and not so far from the shore ($\sim 100m \div few\ km$). Devices in this location are often moored to the seabed, which gives a suitable stationary base against which an oscillating body can work. This typology is a compromise between the others 2 configurations cause it tries to avoid the disadvantage of the shoreline being in more deep water where waves have more quantity of energy, and doesn't need too long moorings. On the other hand the installation cost results higher and devices have to hold up the higher load from the waves.

Offshore devices

Offshore devices are generally in deep water (usually more than 50 meters) so they can harvest the largest amounts energy because of the higher energy content in deep water. However, devices are more difficult to construct and maintain, and need to be designed to resist against more extreme conditions adding cost to construction because of the greater wave height and energy content in the waves. Other problems are found in the high loss for the length of cables to transfer the energy, and the interference that can create to navigation. Despite this, with more powerful waves floating devices in deep water offer greater structural economy .

A useful thing to know is that the higher part of wave energy contained in the movement of the water is closed the surface of the sea: up to 95 per cent of the energy in a wave is located between the water surface and one-quarter of a wavelength below it .

1.4.2 Type classification

Wave energy converters can be classified in three predominant types :

   a) Attenuator

   b) Point absorber

   c) Terminator

Attenuator

This type of converters lie parallel to the main wave directions so they ride the waves. An example of this type is the Pelamis, developed by Ocean Power Delivery Ltd. Later will be explained this technology more specifically.

Point absorber

The wave directions for this kind of devices is not important because of their small size adapted to the incident wavelength . They can be submerged under the sea surface exploiting the differential pressure, or they can float on the surface going up and down on the water.

Terminator

These devices lie perpendicular to the predominant wave direction so physically they intercept waves.

1.4.3   Modes of operation

Another classification can be done on the modes of operation on what the energy conversion is based:

Oscillating water columns

These converters consist in a chamber with an opening to the sea below the waterline where the level of the water goes up and down following the see waves profile. This variation of water level is translate in a differential pressure inside the chamber that generally activate the turbine.

Hinged contour devices

This type of device follows the motion of the waves; it creates power using the motion at the joints. It is commonly moored slackly to hold it in place.

Buoyant moored devices

This type of device floats on the surface of the water or below it. The energy is extracted during the oscillations from the bottom to the top or the opposite. It is moored to the seabed by either a taught or loose mooring system.

Overtopping devices

An Overtopping device captures sea water of incident waves in a reservoir above the sea level, then releases the water back to sea through turbines [10].

1.5 Existing technology applicable to SRG

1.5.1 Point absorbers

The point absorber is a type of wave energy device that could potentially provide a large amount of power in a relatively small device, compared to other technologies. While there are several different designs and strategies for deploying these types of devices, they all work in essentially the same manner. Point absorbers are relatively small compared to wave length, and may be bottom mounted or floating structures. The vertical motion of the buoy is utilized to alternate the compression of a gas or liquid in some form of container, converted into rotational movement of the power generator, or converted in other similar ways.

Single sensor

In these type of systems a buoy oscillate for the wave motion respect of a fixed reference system. One type can be a buoy connected with a cable, in tension by a spring, to a structure fixed on the bottom of the sea.

The relative motion between the buoy and the bottom of the sea supply a machine for the conversion and this one can be an LSRG (Linear Switched Reluctance Generator)
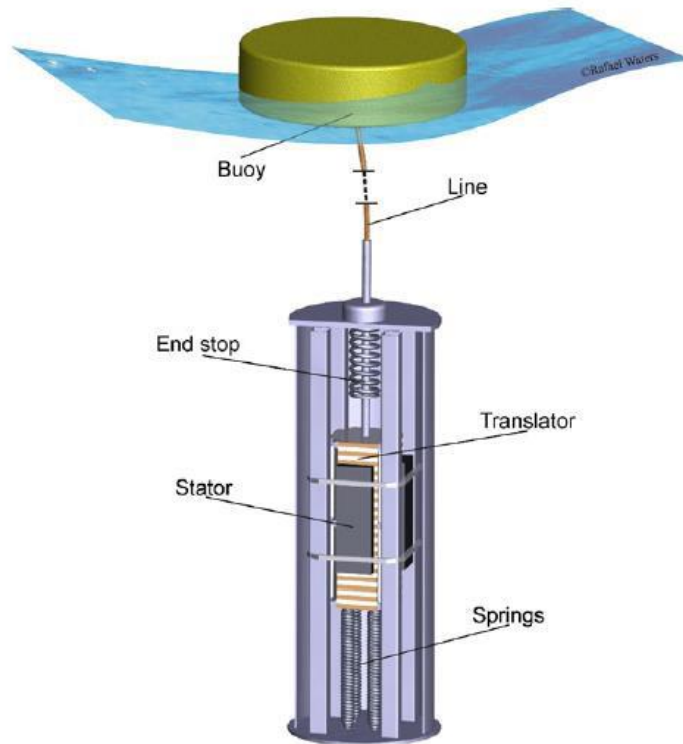

Figure 1.8: Point absorber single sensor

Double sensor

The single body structure has the limit of the distance between the surface and the bottom of the sea, moreover this distance is not constant but can vary by the tides.
A different way was thought to use the relative motion between two structures oscillating in different manner.

1.5.2 Archimede Wave Swing (AWS)

According to Archimedes principle, when an object is emerged in a fluid, a force acts on the object which forces it upwards. This force is known as the buoyant force and is equal to the weight of the fluid displaced by the object. The weight of the displaced fluid can be found by the formula W = mg, where 'm' is the mass and the 'g' the gravitational force.

It is to note that the buoyant force does not depend on the weight or shape of the object, but on the mass of the fluid displaced. Also, when the density of the object is equal to the density of the fluid, the object will neither float or sink.

The Archimedes wave swing is a remarkably simple and elegant solution to tidal power generation. This wave energy converter is a cylindrical shaped buoy which is submerged and tethered to the ocean floor. Moored to the seabed, this generation unit has got only one moving part, the floater unit. The floater unit is an air-filled device which is connected to a lower fixed cylinder.

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The Archimede Wave Swing is a system based on the undulating movement completely submerged developed in Holland. It consist in an oscillating top part and a fixed base. The buoy is pushed to the bottom by the water wave weight when it pass on the structure during its peak. When the peak is passed the buoy moves to the surface. The motion supply an LSRG (for example) while the air contained in it react as a spring pushing the buoy to the surface.
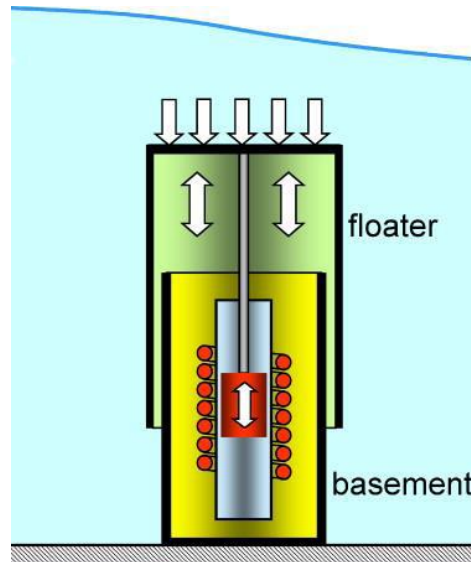

Figure 1.9: AWS

1.5.3 Oscillating water column (OWCs)

This is the relevant devices in once that use a turbine for the energy conversion, with the largest number of installations and life expect. The idea was born in 70's. As already said and shown in figure 1.10 this device consist in a chamber moored to the seabed and partially submerged with an opening to the sea below the waterline. Waves produce inside the chamber a variation of water level that is reflected in a variation of air pressure inside the chamber. This variation of pressure activate a turbine both when the water level is going up and down. The bidirectional flow of air involve that the turbine has to be realized in order to turn in the same direction, independently from the wind flows. For this reason usually *Wells* turbine are utilize in OWCs. The dimension of the chamber is important and has to be done based on the location where the device will be install, so in relation of the wavelength and typical period of waves that will find. OWCs can be installed onshore preferably on rocky shores; nearshore in up to 10m of water; or offshore in 40-80m deep water. They can be moored on the seabed or connected with a feeble fixing that consent a reply to the variation of water medium level. The moored devices contained the largest amounts of energy cause the resistance to the waves from the device is higher. However if there will be a high variation of the average sea level some problems with this devices can be presented, while feeble fixing consent a major flexibility. Also the cost are different cause, as easy to understand, the mobile devices are cheaper than fixed, cause they don't need strong foundations that need a fixed one. The OWCs category contain different devices inside itself but everyone is based on the principle of Oscillating water column. There are two big OWC in Europe: *Pico* (in Azoras, Portugal) of 400 kW, and Limpet (Land Installed Marine Power Energy Transmitter ,Islay, Great Britain , 2000) of 500 kW . These type of OWC have the air column excavated and built onshore. In figure 5.3 is shown an example. Other OWC are in India (Vizhinjam, near Trivandrum, 1999) and Japan (Sakata, 1990) [11] [12] [13].
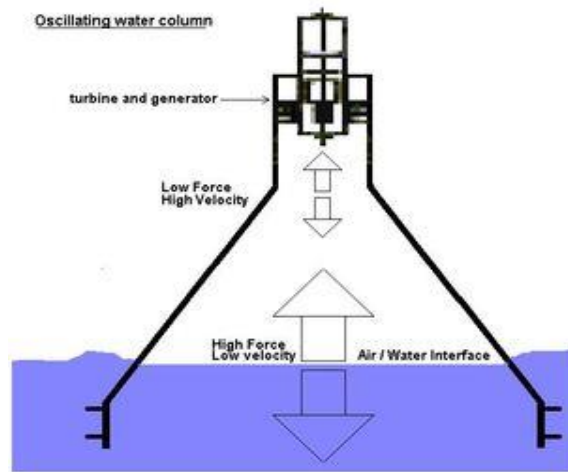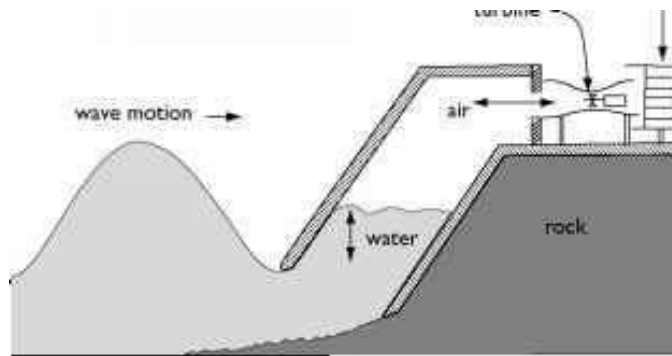
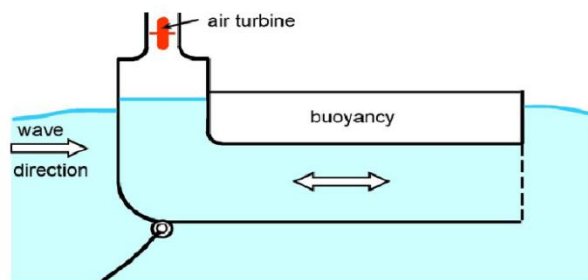**Figure 1.10**: OWCs

Figure 1.11: OWC onshore

Figure 1.12: OWC offshore

2 The Switched Reluctance machine

2.1 Principle of operation of the switched reluctance motor

Consider a 6/4 SRM rotary machine. Consider that the stator poles of the first phase and the rotor poles are aligned as shown in figure 1.9. Apply a current in the first phase. A flux is established through stator poles of the first phase and the rotor poles.
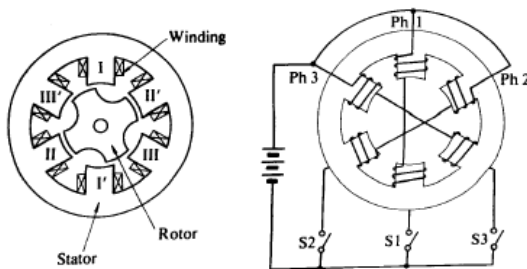

Figure 2.1: A 6/4 SRM when the rotor poles poles are aligned with the 2nd phase
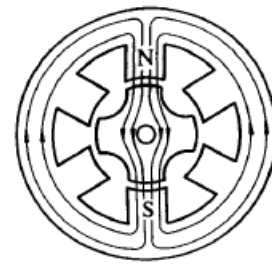
Figure 2.2: A 6/4 SRM when the rotor poles are aligned to the 1st phase

When they are aligned , the stator current in the first phase is turned off and the corresponding situation is shown in the figure above. Now the second phase of the stator is excited pulling the rotor poles toward it in a opposite clockwise direction. This because as told before , the moving part of the motor tends to move in a position of minimum reluctance that corresponds to the aligned situation.
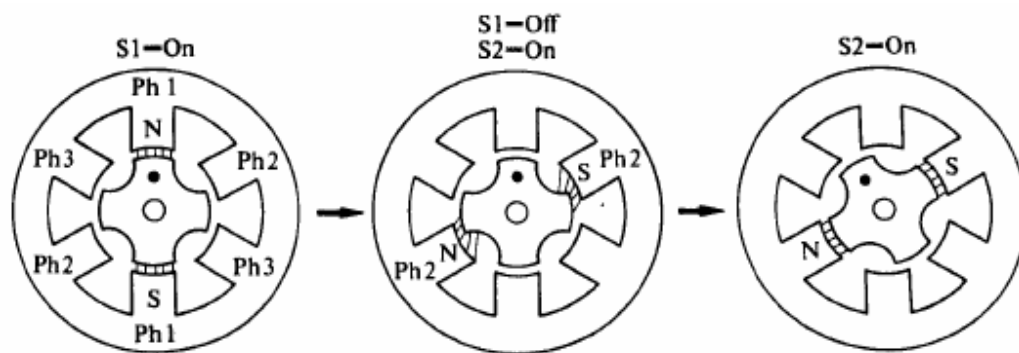

Figure 2.3: Switched on-off of the first and second phase in a 6/4 SRM

Energization of the third phase winding results in the alignment of the rotor poles near it as shown in figure 1.10. In the real operation the switch from one phase to the other is turned on before the rotor poles reach the aligned configuration in order to have an uninterrupted rotation of the rotor.
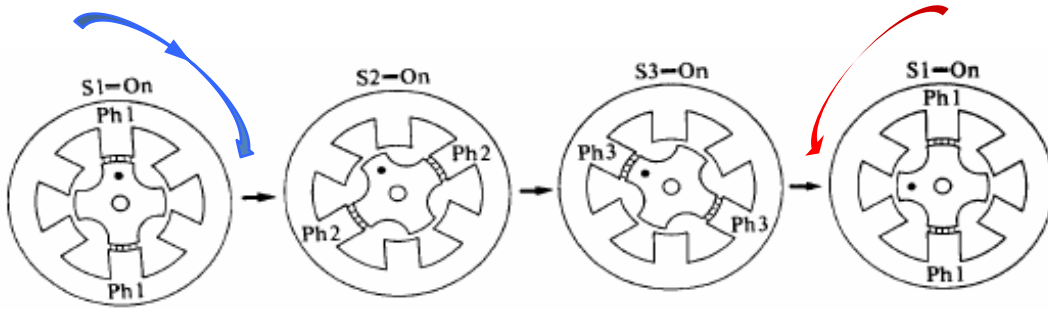
Figure 2.4 : A complete cycle of exciting of the phases in a 6/4 SRM

Rotor rotation as switching sequence proceeds in a three phase SRM, the rotation direction (red line) is opposite to the direction of the excited phase (blue line). The switching angle for the phase current is controlled and synchronized with the rotor position, usually by means of a shaft position sensor.

2.1.1 Torque production

The torque production in SRM can be explained using the elementary principle of electro-mechanical energy conversion [1].
During the conduction of a phase the torque tends to move the rotor in the direction that minimize the reluctance , causing at the same time an increment of the phase inductance as already said.
So a positive torque can be obtained supply each phase when the inductance value is increasing. This process is explain by the principle of virtual works and it's possible to find a relationship between the electromagnetic torque and the variation of magnetic energy. In particular

$$T_{em} = \left[\frac{dW'}{d\theta}\right]_{i=const}$$

Where T_{em} is the electromagnetic torque , W' is the magnetic co-energy that represents the area under the magnetization curve at the position ϑ^* from $i = 0$ to $i = i_k$ (fig. 1.12)

$$W' = \int_0^{i_k} \Psi \, di$$

Where Ψ is the flux linkage.
In the same way is define the energy storage in the magnetic field as
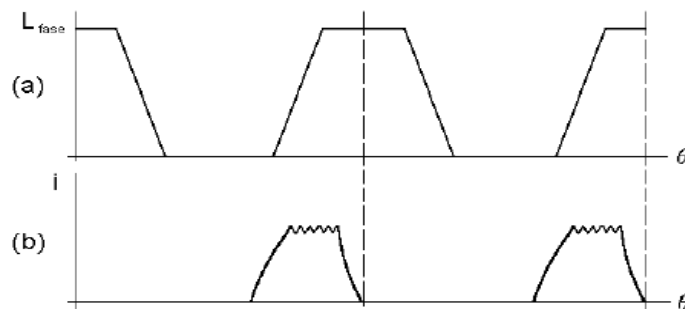
$$W_f = \int_0^{\Psi_k} i \, d\Psi$$

Figure 2.5: Profile of the inductance phase L (a) and profile of the current (b)

The inductance profile shown in figure 1.11 has a value during the unaligned position that seems zero but will be a different value, less than the aligned position but not zero.
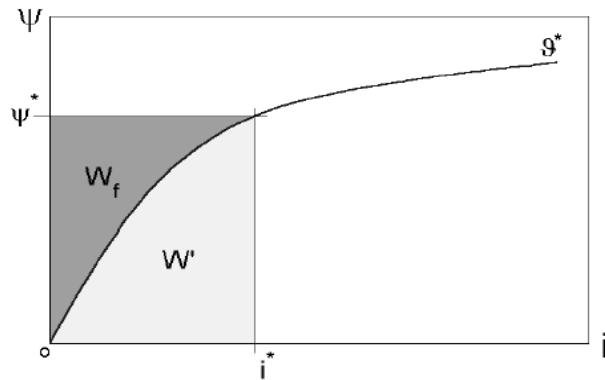

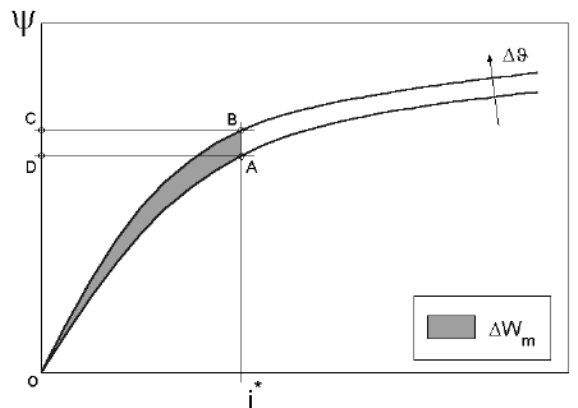**Figure 2.6**: Magnetic energy and co-energy in the plane $\Psi - i$

Figure 2.7: Infinitesimal movement $\Delta\theta$ with an energy conversion of ΔW_m

From the equation, the mechanical work ΔW_m is the difference between the energy absorbed without the energy loss and the variation of ΔW_f of the storage energy , and it results:

$$\Delta W_m = T \, \Delta\theta$$
$$= \Delta W_e - \Delta W_f$$
$$= ABCD - (OBC - OAD)$$
$$= (ABCD + OAD) - OBC$$
$$= OAB$$

So not all the energy is converted in mechanical energy but there is some energy that is stored in the field.

2.1.2 Energy Ratio

The motor is better exploitation if the difference of flux from the unaligned position Θ_u and the aligned position Θ_a is higher. This is obtained if the $L_a \gg L_u$ and if there is a high saturation of the magnetic circuit for high values of currents. If we consider one complete rotation of the machine, the work done is encloses inside the curve in the plane $\Psi - i$.

R is the not converted energy stored.

The energy ratio is defined as

$$ER = \frac{W}{W + R}$$

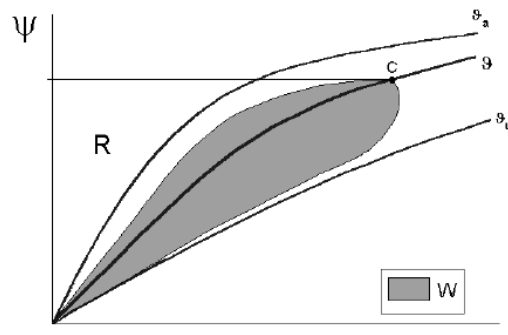If ER is high the exploitation of the machine is higher.

Figure 2.8: W is the energy converted in one complete rotation ; R is the energy that will not be converted

2.2 Linear condition

In linear condition the curves $\Psi - i$ become straight lines [1]. In this condition we have

$$W = W' = \frac{1}{2} L i^2$$

And the relation of the torque becomes

$$T_{em} = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

This is the expression of the Torque for an SRM without magnetic saturation, situation that doesn't exist in the normal function of the machine because it means a low exploitation of the machine.

In linear condition with a movement of the rotor from θ_A to θ_B the ratio $\Delta W_m / \Delta W_e = 0.5$. With saturation and the same movement we have $\Delta W_m / \Delta W_e > 0.5$.
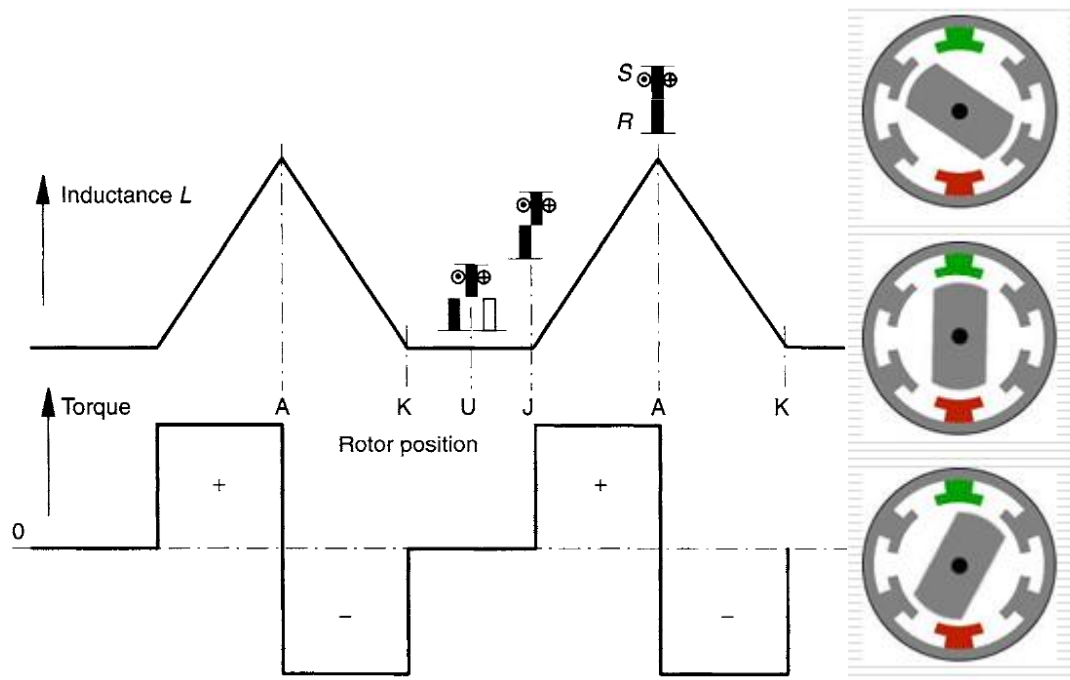
Figure 2.9: Variation of inductance and torque with rotor position; coil current is assumed constant.

The small icons show the relative positions of the rotor and stator poles, with the rotor moving to the right. A=aligned position; U=unaligned position; J=start of overlap; K=end of overlap.

Some considerations on the torque can be therefore outlined:

a) It's proportional to the square of the current and hence, the current can be unipolar to produce unidirectional torque.

b) Since the torque is proportional to the square of the current, it has a good starting torque.

c) Because the stator inductance is nonlinear, a simple equivalent circuit development for SRM is not possible.

d) The torque characteristics of SRM are dependent on the relationship between flux linkages and rotor position as a function of current.
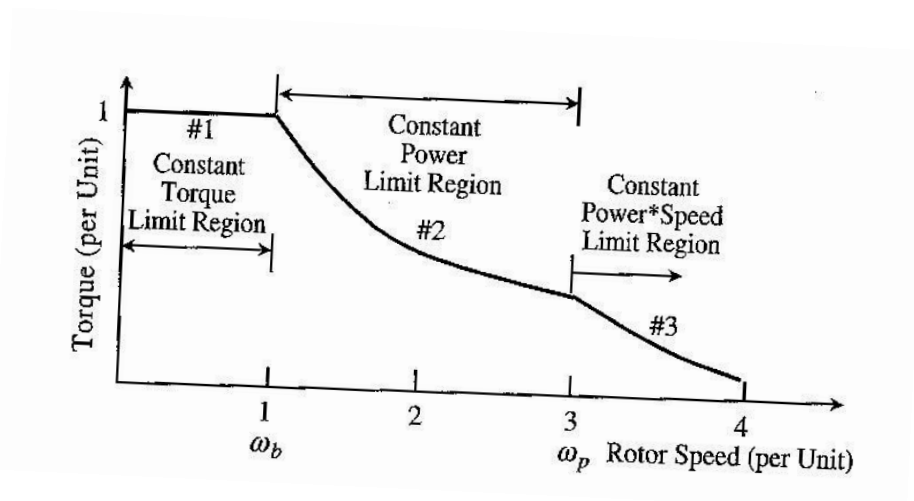
2.3 Torque-speed characteristic

Figure 2.10: Torque-speed characteristic

The figure shows the torque-speed plane of an SRM drive. It's possible to divide it into three regions:

1) constant torque region;
2) constant power region ;
3) constant power*speed region.

Region1: is the region below the base speed ω_b, which is the lowest possible speed for the motor to operate at its rated power. For the small back-emf in this region the current can be set at any desired level by means of regulators such as hysteresis controller or voltage PWM controller.

Region2: is the region where the controller maintains the torque inversely proportional to the speed. In this region, the phase excitation time falls off inversely with speed and so does the current. Because torque is roughly proportional to the square of the current, the rapid fall in torque with speed can be countered by adjusting the conduction angle q_{dwell}. By advancing the turn-on angle to increase the conduction angle until it reaches its upper limit at speed ω_p, the phase current can be increased effectively to maintain the torque production at a high level.

Region 3: In this region, the q_{dwell} upper limit is reached when it occupies half the electrical cycle. The torque in this region is governed by natural characteristics, falling off as $1/\omega^2$.

2.4 Equivalent circuit

Neglecting the mutual inductance between the phases is possible to find an elementary equivalent circuit for the SRM as well explained by Krishnan [2]. The applied voltage to a phase is equal to the sum of the resistive voltage drop and the rate of the flux linkages:

$$v = R_s i + \frac{d\lambda(\theta, i)}{dt}$$

where R_s is the resistance per phase, and λ is the flux linkage per phase :

$$\lambda = L(\theta, i)\, i$$

where L is the inductance dependent on the rotor position and phase current. The general voltage phase equation for any conditions becomes:

$$v = R_s i + \frac{d(L(\theta, i)i)}{dt} = R_s i + \frac{d\lambda}{di}\Big|_{\vartheta=cost}\frac{di}{dt} + \frac{d\lambda}{d\vartheta}\Big|_{i=cost}\frac{d\theta}{dt} = R_s i + L_{inc}(\theta, i)\frac{di}{dt} + k_\omega\frac{d\theta}{dt}$$

Where L_{inc} is the incremental inductance and k_ω is a tensor.
Considering now the linear conditions, where the inductance doesn't depend on the current so $L(\theta, i) = L(\theta)$, the equation becomes

$$v = R_s i + \frac{d(L(\theta)i)}{dt} = R_s i + L(\theta)\frac{di}{dt} + i\frac{d\theta}{dt}\frac{dL(\theta)}{d\theta} = R_s i + L(\theta)\frac{di}{dt} + \frac{dL(\theta)}{d\theta}\omega i$$

The first term is the resistive voltage drop ,the second term is the inductive voltage drop, and the third one is the induced emf, very high for high value of ω.
Is now possible to substitute the flux linkages in the voltage equation and multiplying with the current results in instantaneous input power :

$$p_i = vi = R_s i^2 + L(\theta, i)i\frac{di}{dt} + \frac{dL(\theta, i)}{dt}i^2$$
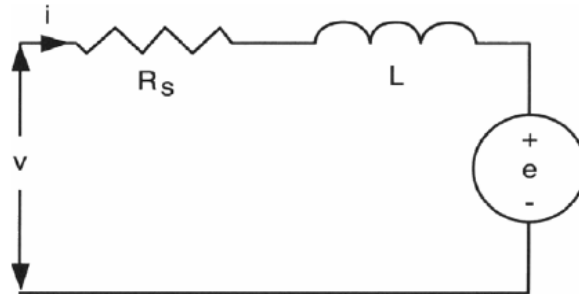

Figure 2.11: Single-phase equivalent circuit of the SRM.

The last term may be write in a different way to be physically interpretable:

$$\frac{d(\frac{1}{2}L(\theta, i)i^2)}{dt} = L(\theta, i)\, i\, \frac{di}{dt} + \frac{1}{2}i^2\frac{dL(\theta, i)}{dt}$$

substituting this in the above equation :

$$p_i = R_s i^2 + \frac{d(\frac{1}{2}L(\theta,i)i^2)}{dt} + \frac{1}{2}\frac{dL(\theta,i)}{dt}i^2$$

where pi is the instantaneous input power. The time can be write in terms of the rotor position and speed like:

$$t = \frac{\theta}{\omega_m}$$

And substituting in the equation, the air gap power results:

$$p_a = \frac{1}{2}i^2\frac{dL(\theta,i)}{dt} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta}\frac{d\theta}{dt} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta}\omega$$

The air gap power is the product of the electromagnetic torque and rotor speed:

$$p_a = \omega T_{em}$$

from which is possible to obtained the torque (in linear condition) by equating these two equations:

$$T_{em} = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta}$$

2.5 The converter

The torque in SRM drives is independent of the excitation current polarity; for this reason the SRM drives require only one power switch per phase winding. In the following only one type of converter is considered, the same one which is used in the simulations [2].

Asymmetric bridge converter

The figure that we consider shows only one phase of the SRM because the rest of the phases are similar connected.
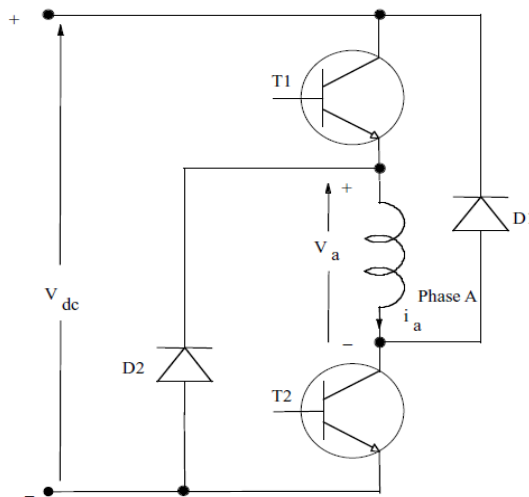

Figure 2.12: Asymmetric bridge converter

Turning on transistors $T1$ and $T2$ enable the supply of the phase A by the DC voltage Vdc. When the current rises above the commanded value, $T1$ and $T2$ are turned off. After this the energy stored in the motor winding of phase A will keep the current in the same direction until it is depleted. Diodes $D1$ and $D2$ will become forward biased leading to the source and a simultaneous current decrease reaching the value below the reference one.

If a current Ip is desired during the positive inductance slope for motoring action, the A-phase current command is generated with a linear inductance profile. Phase advancing both at the beginning and during commutation are neglected. The current command is controlled with a feedback loop in which the current reference value is compared with the real phase current. The current error goes through a hysteresis controller with a current range of Δi. When the current error exceeds $-\Delta i$, the switches $T1$ and $T2$ are turned off simultaneously so diodes $D1$ and $D2$ take over the current and complete the path through the dc source.
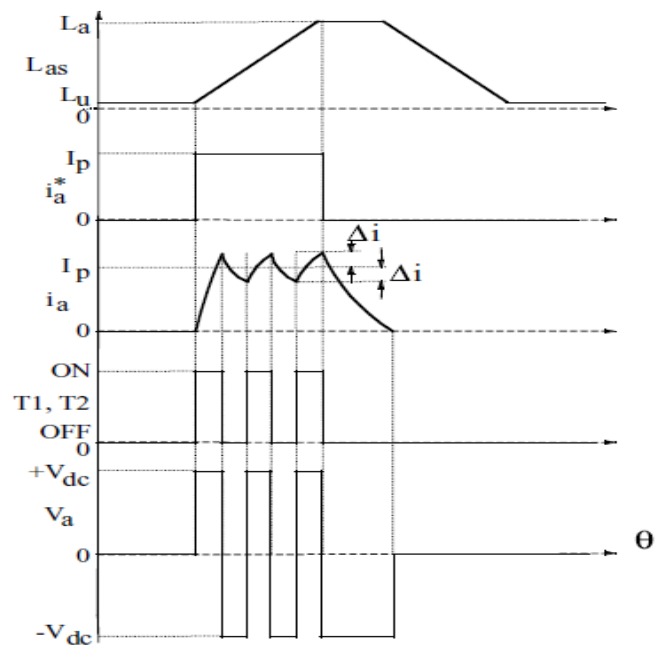

Figure 2.13: Profile of L,I,SW output and V inside the converter, 1st strategy.

The voltage of phase A is then negative and will equal the source voltage, Vdc. During this interval, the energy stored in the machine inductance is sent to the source, thus exchanging energy between the load and source repeatedly in one cycle of a phase current.
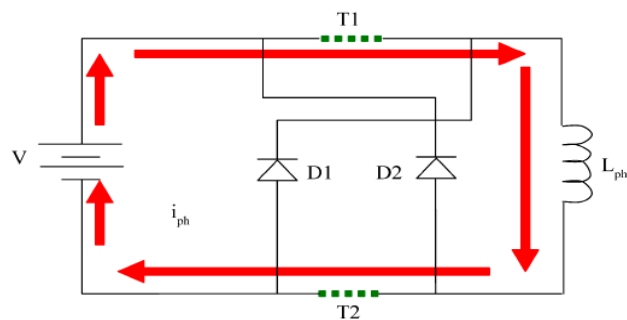

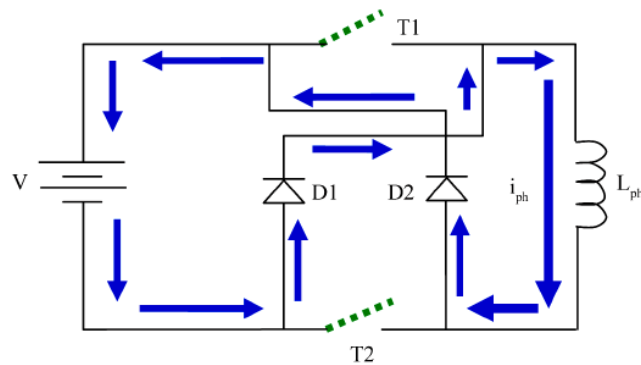**Figure 2.14**: Current path with T1 and T2 ON

Figure 2.15: Current path with T1 and T2 OFF

However this control strategy (strategy I) causes more ripples into the dc link capacitor that means that its life is reduced and also the switching losses are increased due to frequent switching. These can be ameliorated with an alternate switching strategy.

This second strategy can obtain (strategy II) Turning off $T2$ only: the current will continue to flow through $T1$, phase A, and $D1$ and the voltage across the winding becomes zero.

The current will pass from $Ip+\Delta i$ to $Ip-\Delta I$ in a time greater than using the previous strategy and also the switching frequency is reduced and hence the switching losses. When the current command goes to zero, T1 and T2 are turned off simultaneously. During this interval , the voltage across the winding becomes $-Vdc$ as long as D1 and D2 conduct and thereafter the winding voltage is zero.
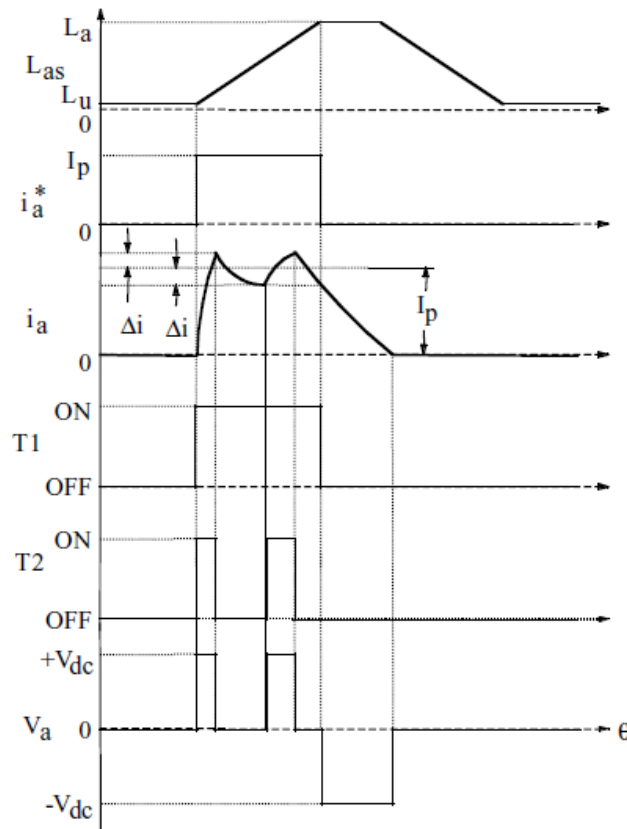

Figure 2.16: Profile of L,I,SW output and V inside the converter, 2nd strategy.

3The Switched Reluctance Generator

3.1 Principle

The switched reluctance machine can operate as a generator by changing the firing angles [3].

In generating operation the angles are chosen in order to have the flowing of the current when $\frac{dL}{d\theta} < 0$. The circuit equation for one phase become:

$$v = Ri + \frac{d\Psi}{dt} = Ri + L\frac{di}{dt} + i\frac{d\theta}{dt}\frac{dL}{d\theta} = Ri + L\frac{di}{dt} + e$$

where

$$e = \omega i \frac{dL}{d\theta}$$

is the back-emf and

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

is the rotor speed as already said in the first chapter. Is easy to understand that the sign of e is determined by $dL/d\theta$. When $dL/d\theta < 0$ the back-emf is negative and it tends to increase the current and convert the mechanical power into electrical power. The figure 2.1 shows this concept of the different supply during the inductance profile.
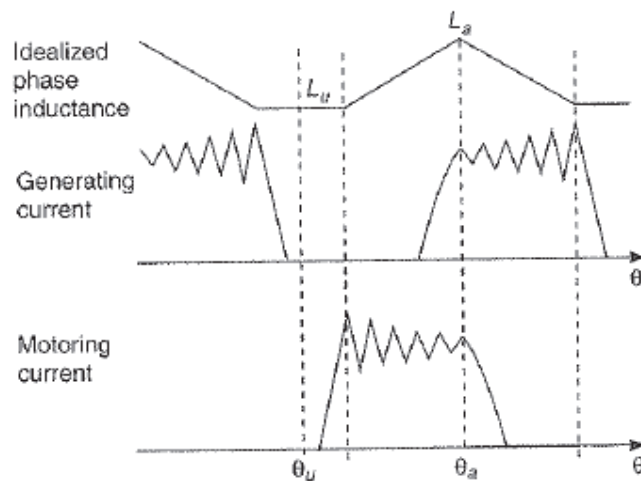

Figure 3.1: Phase inductance and generating current

This figure shows the circuit diagram of a generator with one phase-leg and it is possible to see that both the converter and load are connected to the same d.c.-bus.
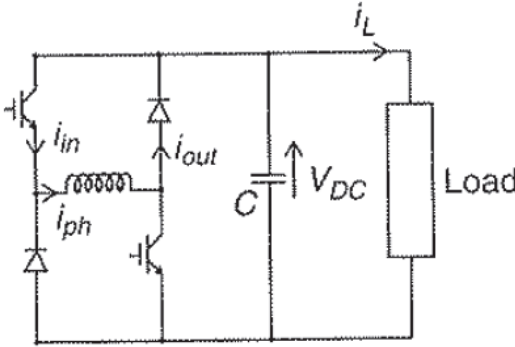

Figure 3.2: Generator circuit for one phase

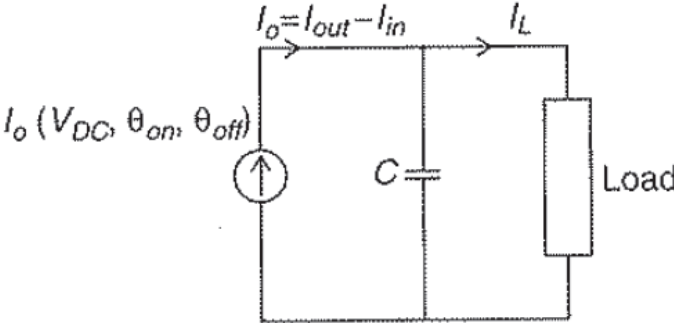This other figure shows the energy flow in the circuit

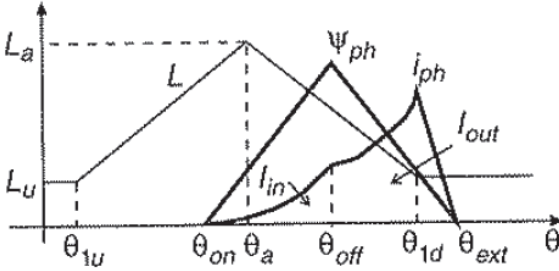**Figure 3.3**: Simplified circuit diagram showing energy flow

Figure 3.4: Simplified circuit diagram showing energy flow

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Referring to these figures is possible to calculate the average value of the currents in the following way:

$$I_{in} = \frac{1}{\Delta\vartheta} \int_{\theta_{on}}^{\theta_{off}} i_{ph} \, d\theta$$

$$I_{out} = \frac{1}{\Delta\vartheta} \int_{\theta_{off}}^{\theta_{ext}} i_{ph} \, d\theta$$

$$I_0 = I_{out} - I_{in}$$

Where I_0 is the net generated current.

The excitation penalty is defined as

$$\varepsilon_p = \frac{I_{in}}{I_{out}} = \frac{I_{in}}{I_0 + I_{in}}$$

In the next figure is shown an example of idealized current waveforms with single-pulse control.

Definition of the angles:

θ_{on} Turn-on angle

θ_a Aligned position

θ_{off} Turn-off angle

θ_{1d} Angle at which pole overlaps ends

θ_{ext} Angle at which the flux reaches zero
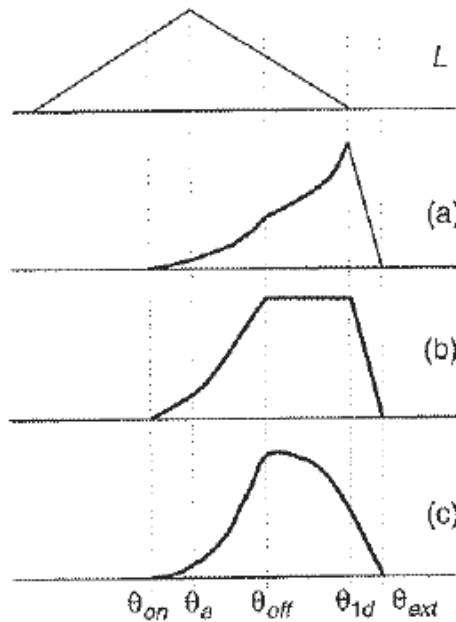

Figure 3.5: Idealized current waveform

Between θ_{on} and θ_{off} the current is flowing through the phase so the transistors T1 and T2 are closed and the diodes are off while after θ_{off} the current is turned off so T1 and T2 are opened and diodes D1 and D2 are on cause the current close its circuit through them..

The peak of current is reached at θ_{off} or θ_{1d}. In the case (a) the current increases after turning off the switches at θ_{off}, when the back-emf in the coil is greater than the d.c.-bus voltage V_{DC}.

In the second case (b) the back-emf and V_{DC} have the same value so the current is constant until the pole overlap ends in θ_{1d}. In the third case (c) the back-emf is smaller than V_{DC} so the current decreases after θ_{off}.

From θ_{on} to θ_{off} the d. c. power source supplies the excitation power through the converter to the machine, and it's stored in the airgap as magnetic energy. After the switches are turned off regenerating current flows through the freewheeling diodes returning the generated power into the d. c. power supply until the current vanishes at θ_{ext}.

If the generated power P_{gen} is greater than the excitation power from the d. c. bus-voltage, the system has net generated power by converting mechanical power into electrical power. The power generated will flow to the grid so the system needs an inverter to convert the power from DC to AC.

In many application, like the model that will be explained in the next chapter, all or part of the energy is stored inside batteries.

The waveform of the first case (a) has the smallest ε and (c) the largest. If the net generated current is the same for all three cases , the waveform of (a) is preferred cause the smallest ε reduces losses.

In the figure 2.6 the loci of the current on the $i - \Psi$ plane is shown , the current peak value being the same. The energy converted is proportional to the area enclosed by the loci. When the peak value is limited , (b) is expected to generate the largest energy.
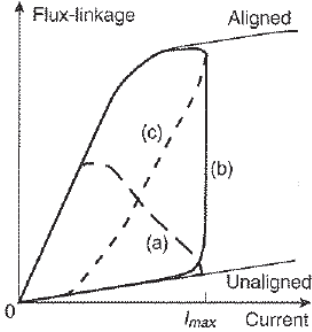

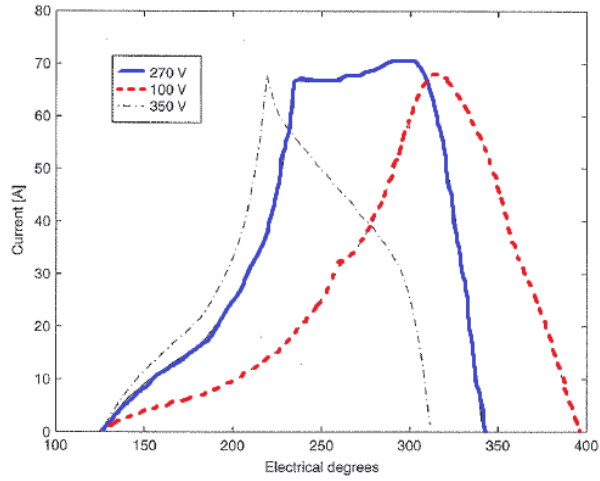**Figure 3.6**: Energy conversion loop

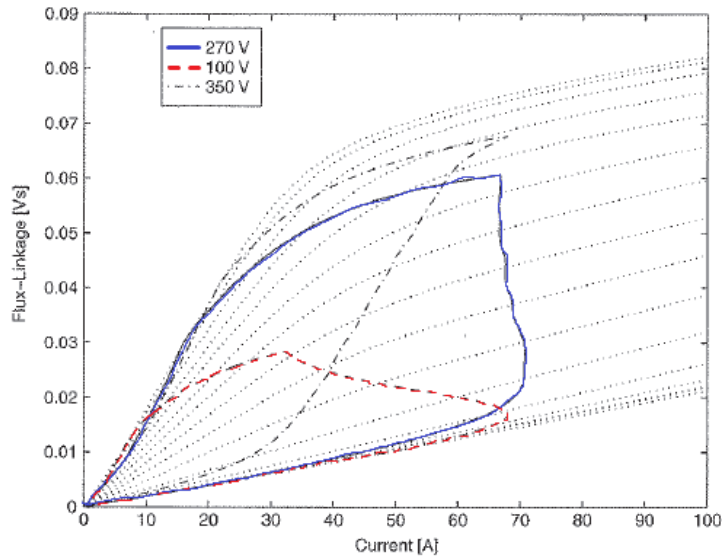**Figure 3.7**: Example of current waveform

Figure 3.8: Example of energy-conversion loops

If R is negligible, the equation becomes

$$v = L\frac{di}{dt} + e$$

With $v = V_{DC}$.

When $e = V_{DC}$ at the rated current , ω is called the base speed (Miller, 1993) and in this case the current is constant during the period from θ_{off} to θ_{1d} provided $\theta_{off} > \theta_a$.

The current waveform of SRG may be controlled as follows:

- Like the case (a) when the generating current is small and the peak current is less than its maximum value, in order to minimize the losses. V_{DC} is maintained at the nominal value.

- Like the case (b) after the peak current reaches its maximum value in order to utilize the maximum energy available for a given maximum current.
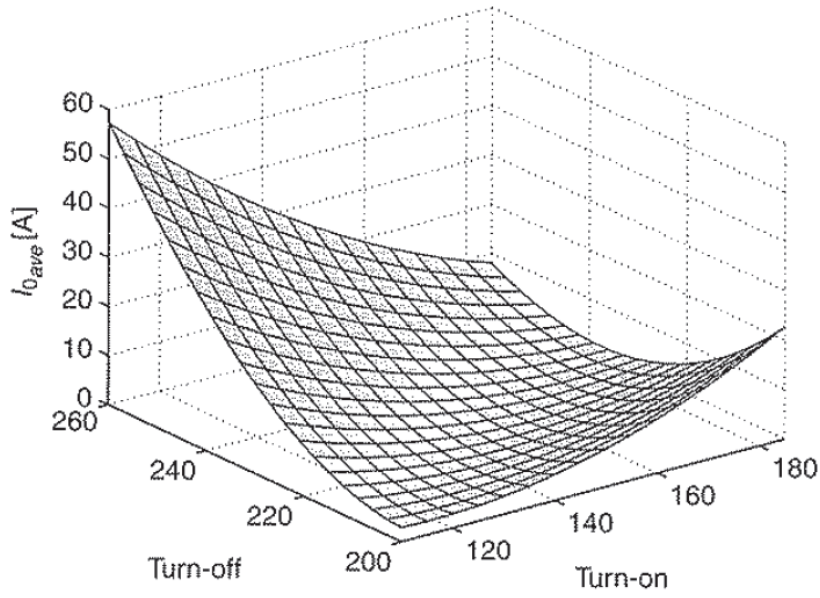

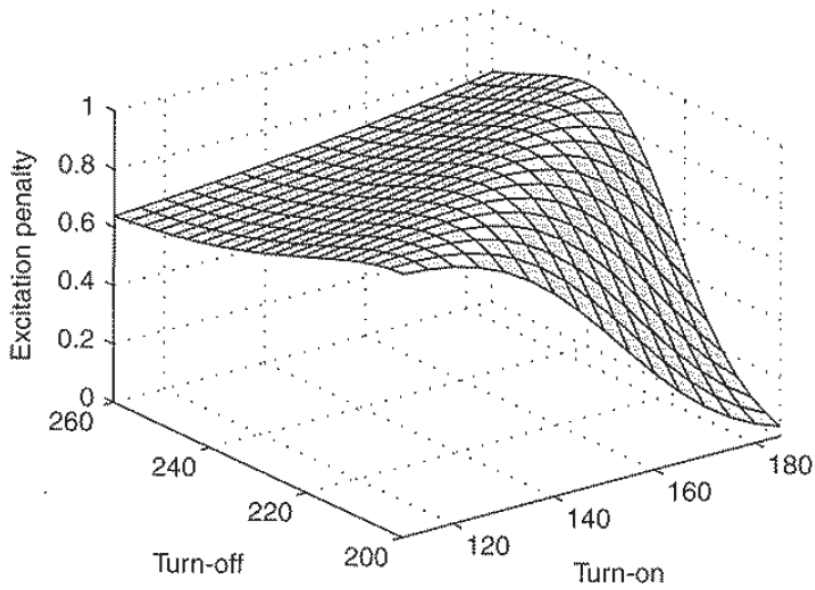**Figure 3.9**: I_0 vs switching angles (in electrical degrees)

Figure 3.10: excitation penalty vs switching angles (in electrical degrees)

3.2 Inductance profile for different models machine configurations

Is now explained a description of inductance profile to enable a proper definition of the firing angles for different type of machine that will be used in the simulation model.

3.2.1 Switched Reluctance machine 6/4 (6 stator poles, 4 rotor poles)

Let consider a switched reluctance machine 6/4 (6 stator poles, 4 rotor poles) with 3 phase windings on the stator, one every 2 poles.
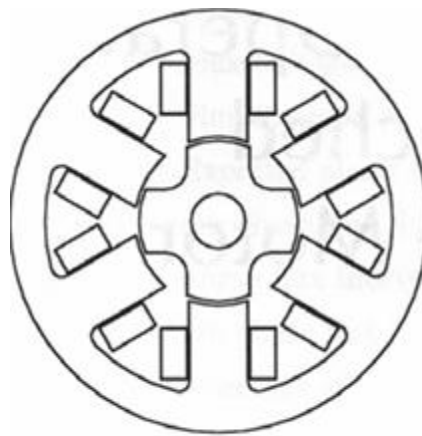
6/4 Pole

Figure 3.11: 6/4 SRG

The step angle, that is the rotation angle for each torque pulse, is defined as:

$$\varepsilon = \frac{2\pi}{m * N_r}$$

Where

m is the phase number

N_r is the number of rotor poles

$m * N_r$ are the pulses/revolution

So in this model it will be

$$\varepsilon = \frac{2\pi}{3 * 4} = 30°$$

Now to describe the inductance profile we have to consider that at the initial condition the rotor poles are aligned with the stator poles of the first phase like in the figure 2.9. So the initial conditions for each phase will be the angle between the stator and the corresponding rotor poles. The stator pole arc

α_s is $2\pi/N_s$ while the rotor pole arc α_r is $2\pi/N_r$ so they will be respectively $60°$ and $90°$. This mean that the initial condition for the first phase will be $0°$, for the second $-30°$ and for the third $-60°$.

The inductance reproduces the rotor reluctance variation. This means that, being $\alpha_r = 90°$, between the maximum and the minimum value of inductance (aligned and unaligned position) there are $45°$ $(90/2)$.

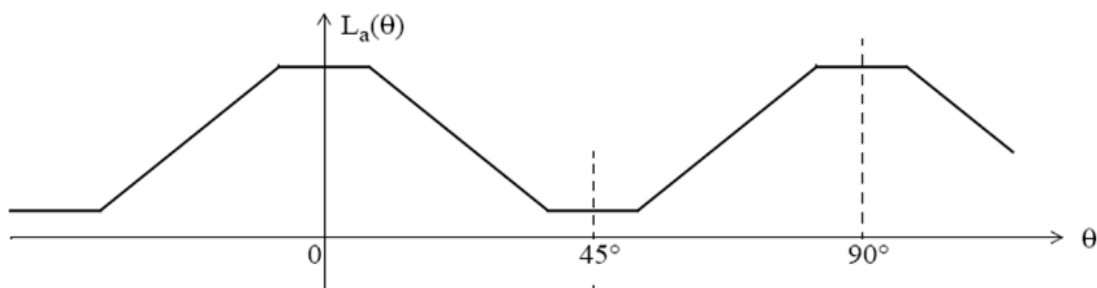The approximate inductance profile in linear condition for the first phase is reported in fig. 2.12

Figure 3.12: profile of inductance in a 6/4 SRG

The profile for the second and the third phase will be exactly the same shifted by 30 and 60 degrees.

As in generating operation the firing angles are chosen so that the current flows when $dL/d\theta < 0$, so in this case the firing angles will be chosen between $0°$ and $45°$.

Then the conducting intervals $(\theta_{off} - \theta_{on})$ can be larger or smaller [4] [5].
A large conducting interval results in high peak flux-linkage value and consequently increased iron loss. A reduce conducting interval means that iron loss is reduced, however peak and rms current are increased and consequently copper loss is increased. Optimal efficiency operation is attained at a best balance between iron and copper loss.

Being the step angle

$$\varepsilon = \frac{2\pi}{m * N_r} = 30°$$

And calling β_r, β_s the rotor polar arc and the stator polar arc, the conditions to impose in order to have eligible value are :

$$min(\beta_r, \beta_s) \geq \varepsilon$$

$$\beta_r + \beta_s \leq \frac{2\pi}{N_r}$$

$$\beta_r \geq \beta_s$$

The first one is necessary to avoid torque holes in a complete rotation, that are intervals where the machine doesn't produce torque.

The second one is necessary to avoid that one stator pole could overlap with two rotor poles at the same time because this situation would provide magnetic path that don't produce torque.

The third one is necessary for construction needs and also, with the second condition, provide the maximum ratio between the aligned and unaligned inductance that maximize the torque production.

After this definitions is possible to understand that the inductance will have the aligned inductance L_a value for all the aligned period that is proportional to $\beta_r - \beta_s$.

3.2.2 Switched Reluctance machine 8/6 (8 stator poles, 6 rotor poles)

Such configuration consists of 4 phases with two stator poles simultaneously excite to enable the alignment of two rotor poles.
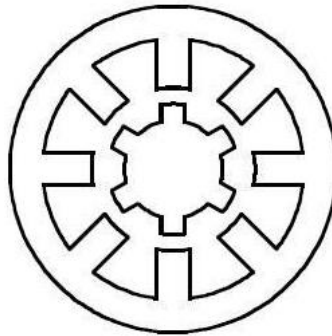
4 Fases 8/6

Figure 3.13: 8/6 SRG

$m = 4$

$N_r = 6$

$N_s = 8$

$m * N_r = 24$

$$\varepsilon = \frac{2\pi}{m * N_r} = \frac{2\pi}{4 * 6} = 15°$$

$$\alpha_s = \frac{2\pi}{N_s} = \frac{2\pi}{8} = 45°$$

$$\alpha_r = \frac{2\pi}{N_r} = \frac{2\pi}{6} = 60°$$

Initial condition: $0°; -15°; -30°; -45°$

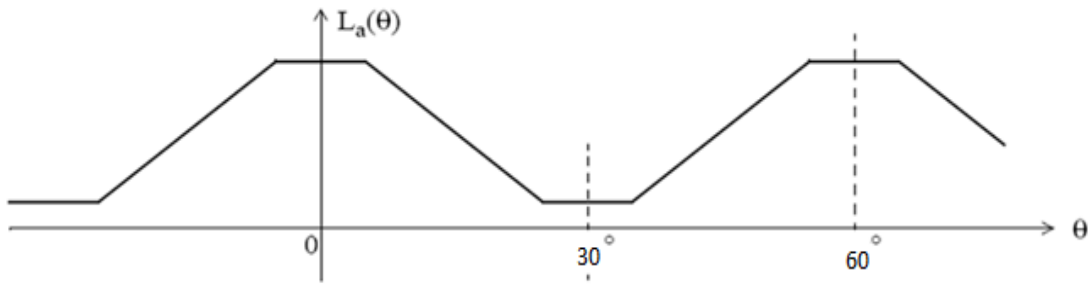L_{max} and L_{min} every $30°$

Inductance profile of the first phase:

Figure 3.14: profile of inductance in a 8/6 SRG

The usable range for the firing angles with generating operation is $0° \div 30°$.

The others phases will have the same profile of inductance translate of $-15°, -30°, -45°$.

3.2.3 Switched reluctance machine 10/8 (10 stator poles, 8 rotor poles)

Such configuration consists of 5 phases with two stator poles simultaneously excite to enable the alignment of two rotor poles.
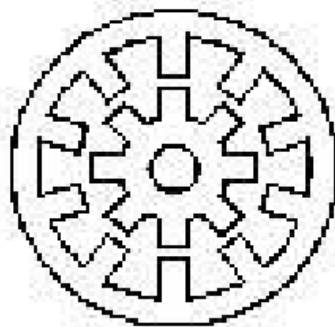

Figure 3.15: 10/8 SRG

$m = 5$

$N_r = 8$

$N_s = 10$

$m * N_r = 40$

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$$\varepsilon = \frac{2\pi}{m * N_r} = \frac{2\pi}{5 * 8} = 9°$$

$$\alpha_s = \frac{2\pi}{N_s} = \frac{2\pi}{10} = 36°$$

$$\alpha_r = \frac{2\pi}{N_r} = \frac{2\pi}{8} = 45°$$

Initial condition: $0°; -9°; -18°; -27°; -36°$

L_{max} and L_{min} every $45°/2 = 22.5°$
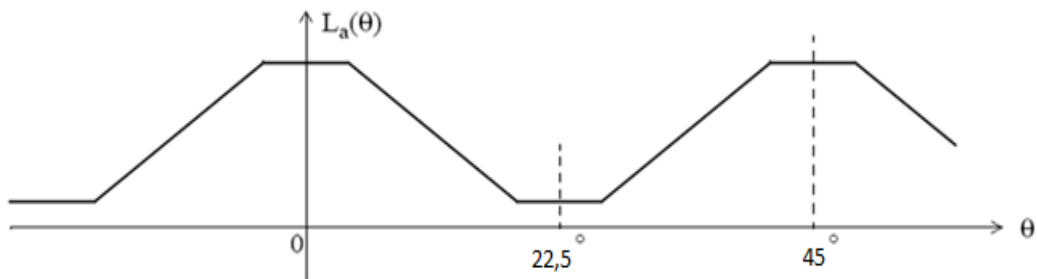
Inductance profile of the first phase:

Figure 3.16: profile of inductance in a 10/8 SRG

The usable range for the firing angles with generating operation is $0° \div 22,5°$.

The other phases will have the same profile of inductance shifted by $-9°, -18°, -27°, -36°$.

4 SRG system modelling

4.1 Implementation

In Figure 3.1 is shown the general layout of the SRG without the connection to the grid side that is implemented inside the converter block for space reasons.
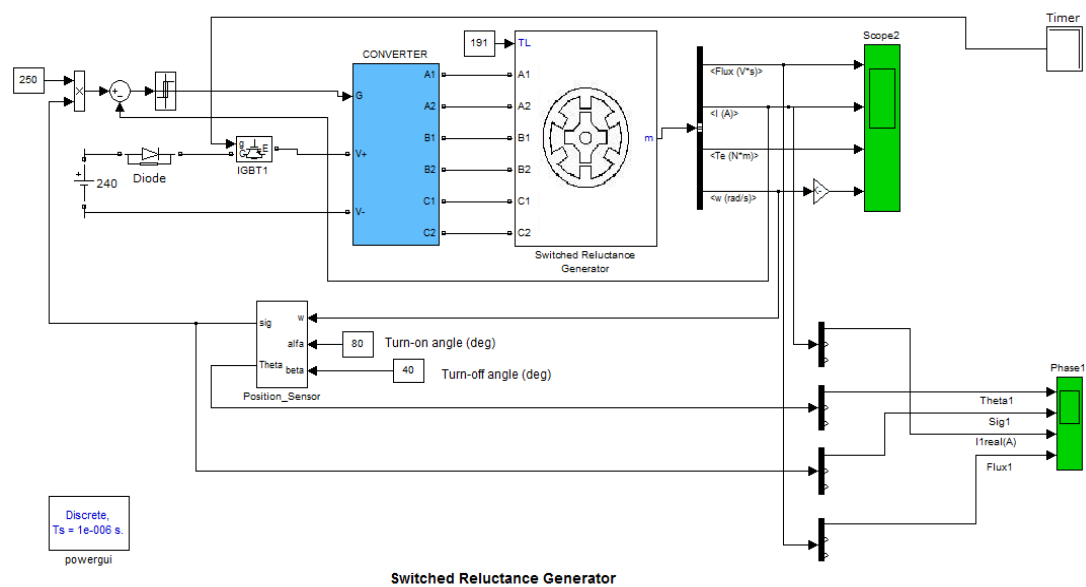

Figure 4.1 : SRG general layout

In this paragraph is explained all the parts of the model, later also the simulations results are shown and the grid side and control is described. As is possible to see in figure 3.1 the machine is a 6/4 poles. The model can be divided in 4 main parts: the external voltage source, the converter, the machine, the position sensor; is now described each one of these part.

The simulations and analysis are done assuming a constant power, torque and speed as in steady state conditions. The model will be improved later in order to conduct the analysis with different torque load starting from an initial speed of zero but results are not discuss in this thesis cause will be a future work where will be possible to apply the waves torque profile.

The mechanical torque input TL provide an angular speed to the shaft, being:

$$P_m = TL\ \omega$$

So from the mechanical characteristic of the machine is possible to study it at different speed. At the beginning the simulations are done with constant value of load torque so with a constant angular

speed. Another group of researcher is studying the wave profile in order to know which angular speed provide to the shaft. The other input is the current that is necessary through the phases to create the magnetic field; this is provided at the beginning from an external DC source voltage that will be disconnected when the capacitor is completely charged and can so becomes itself the DC bus voltage .

4.1.1 POSITION SENSOR

As described in the 2nd chapter the machine has 3 phases on the stator poles and the current is provided in each one during the negative slope of $dL/d\theta$. So fixing the firing angle between 0 and 45 degrees the position sensor block provides the pulse for each phase. The angles 0 and 45 are the value for the first phase but summing these with the initial conditions as explained later also the value for the second and the third phase will figure out.
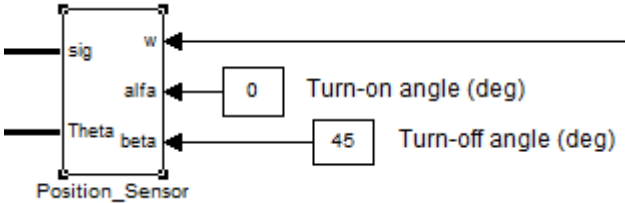

Figure 4.2 : Position sensor block

Later will be explained the choice of the firing angles in order to have the maximum production of power. The figure 3.2 shows the configuration inside the sensor block.
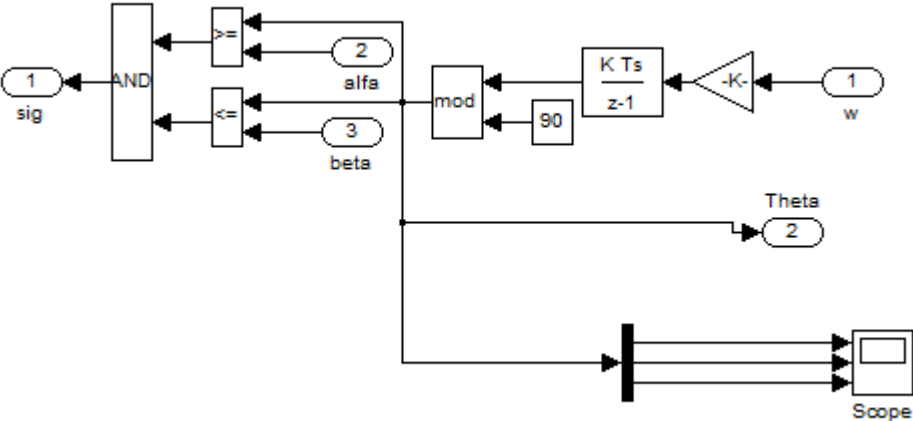

Figure 4.3: Position sensor block configuration

The angular speed ω[rad/s] is multiplied to a constant value, 180/π, to find ω [grad/s] that is integrated to find the angle of each phase between the phase and the closer rotor pole. This means that

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the output will be 3 values, the measures of the rotor poles position respect each phase. To find these the integrator needs a number of initial conditions equal to the number of phases. The machine used for the simulations and analysis is a 6/4 model and it has three phases, so considering the rotor pole alignment with the stator pole of the first phase, as already explained at 2.2, the initial conditions will be $0°, -30°, -60°$. The next figure shows the positions of the rotor poles respect each phase:
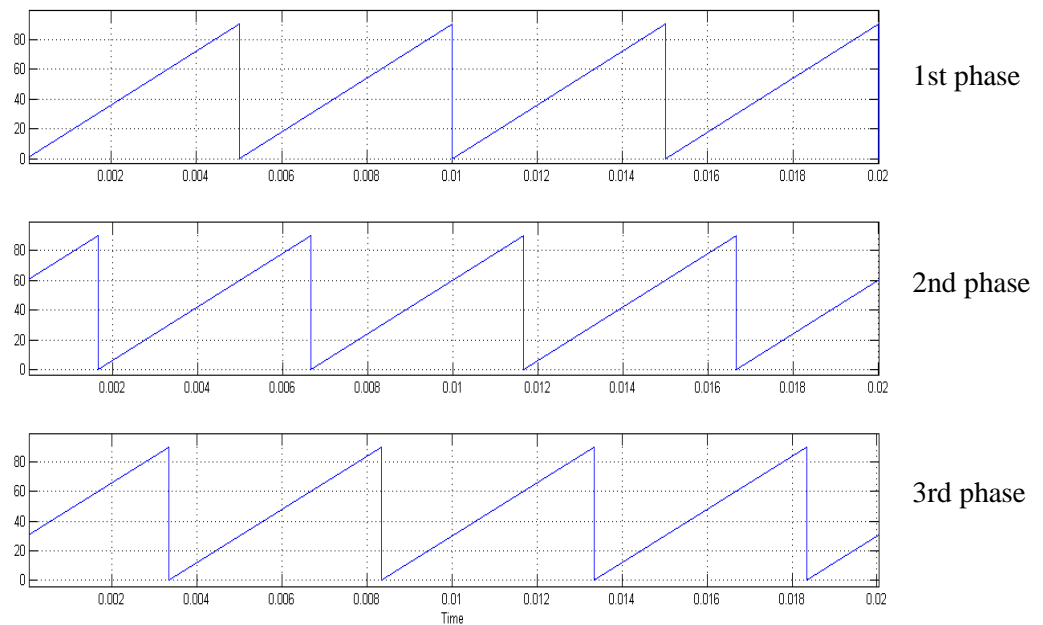

Figure 4.4: angle between the rotor poles and the phases

From the figure is possible to see that the rotor pole respect of the first phase is aligned at the beginning of the simulation, while the one respect the second and the third phases are out of phase respectively of -30 and -60 degrees. The angles can change from 0 to 90: when they reach this value the mod block (modulus after divided) divide them per 90 (the rotor angle) and the value restart from zero in order to use the same value of theta on and theta off, otherwise we should have to change the theta on and theta off angle values every time. Now the angles become the input signals in the Relational Operator block that compares two inputs using the **Relational operator** parameter that you specify. The first input corresponds to the top input port and the second input to the bottom input port.

<= TRUE if the first input is less than or equal to the second input

>= TRUE if the first input is greater than or equal to the second input

So if the angles are greater or equal than alfa and lower or equal than beta the output sig is 1 otherwise it will be 0 ; this is because the logical operator AND is TRUE (1) if all inputs are TRUE. Later the logical operator will be change in OR to be able to anticipate the theta on angle. The figure 3.4 shows the output of the sensor position:
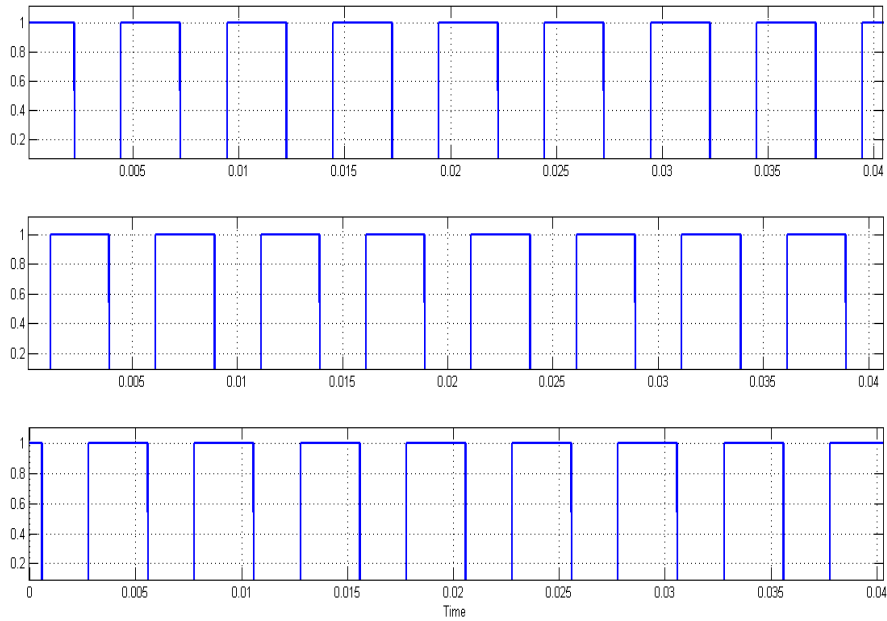
Figure 4.5: output of position sensor block

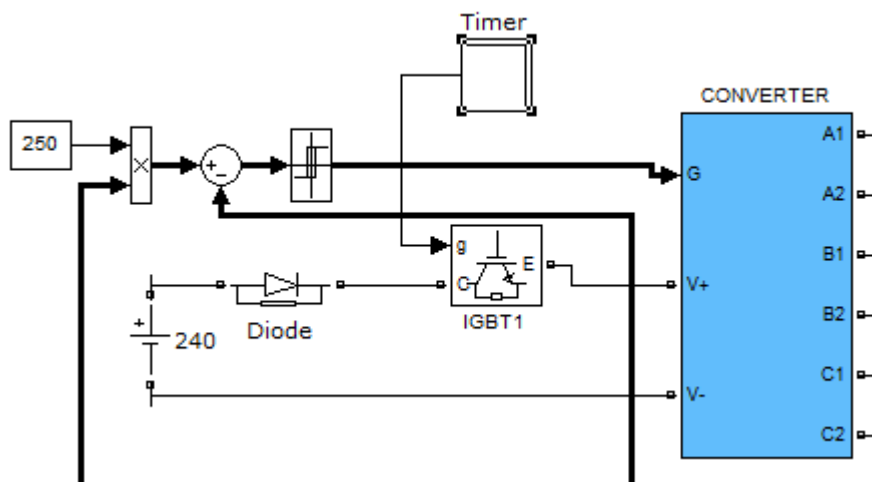## 4.1.2 INITIAL EXTERNAL SOURCE

Figure 4.6: initial external source

The output signal of the sensor position goes inside a product with a constant value that is the reference current to be imposed in the windings. This value is compared with the real value of current that is feed-back from the output of the machine in order to maintain the current at a desired value. The error is now the input of a hysteresis control that output the specified 'on' or 'off' value by comparing the input to the specified thresholds.
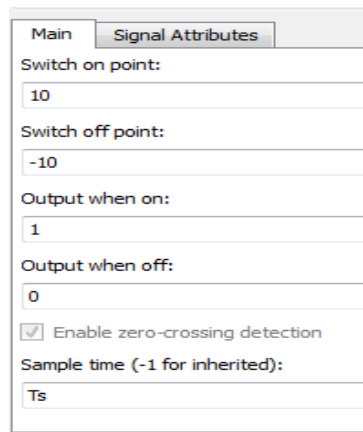
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Figure 4.7: relay parameters

This signal command the switch on/off of the transistor inside the bridge converter in order to increase or decrease the current value. When the difference between the currents become +10 (the real current is lower than the reference value) it switch on and the current starts to increase. When it becomes -10 (real current higher than reference value) it switch off and the current start to decrease. The output when on is 1, when off 0 and it will control the gates of transistors of the converter. The current is provided from an external dc bus voltage how can we see in the general layout and as already said is disconnected when the capacitor across the bridge is charge so after the machine is autosupport.
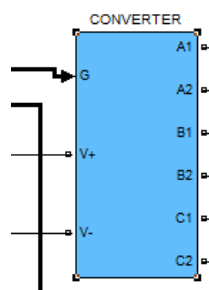
4.1.3 CONVERTER
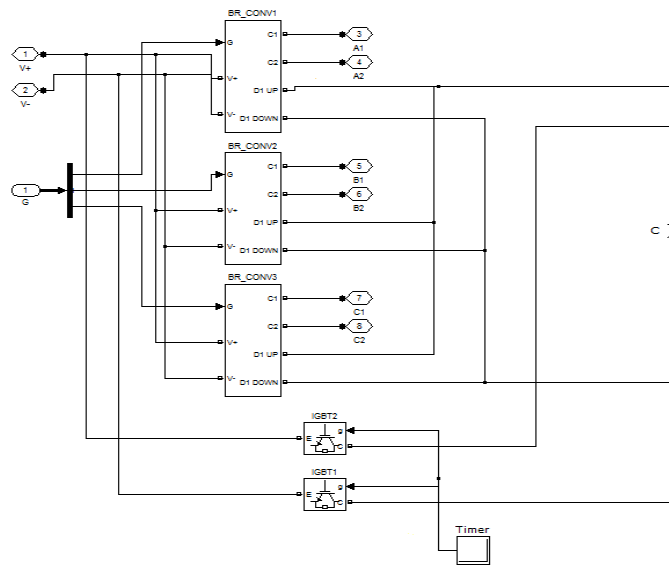

Figure 4.8: converter block

Figure 4.9: converter bridges connected to the capacitor

The converter has three arms connected to the phases of the machine and in parallel to a capacitor where the energy is stored during the generating operation. As already said, when the capacitor charge is complete, the external dc bus voltage is disconnected and the capacitor becomes the source; this operation is implemented with two IGBT commanded by a timer as shown in figure 3.8.

The figure 3.9 shows one of the converter arm:
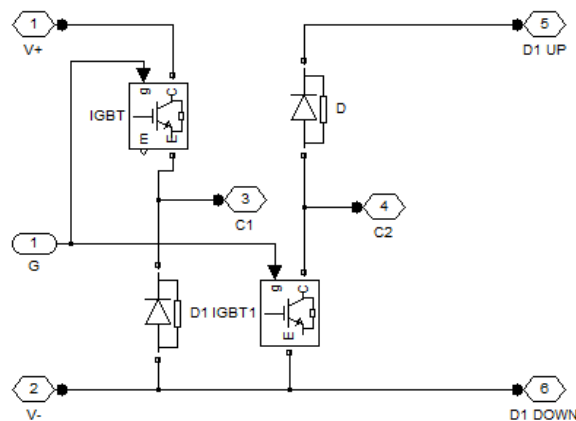
Figure 4.10: one single converter arm

The gate of transistors is commanded by the output of the relay. When the output is 1,the transistor are turned on and the current flows inside the correspondent phase, C1 and C2. This create a back-emf during the negative slope of $dL/d\theta$. They are switched on and off to maintain the current at the reference value and when the angle reaches the θ_{off} value, the transistor are switched off and the

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back-emf charges the capacitor that is connected in parallel, between D1UP and D1DOWN. Figure 3.10 shows one cycle of one phase of the machine.
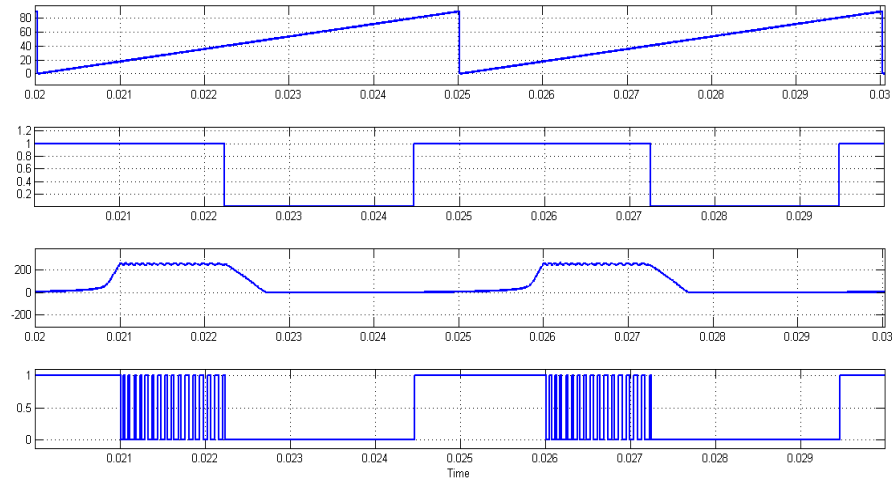
Figure 4.11: profile of one excitation phase

The first profile is the position of the rotor pole respect to the first phase called theta angle; the second is the output of the sensor position that is one during the firing angle period that at the beginning was fixed at 0-45 degrees; the third is the current that flows in the first phase. This one is maintained at 250 A switching the transistors commanded with the output of the relay for the first phase (the fourth profile).

Figure 4.12: current profile and control gates pulses

4.1.4 MODEL OF THE SR MACHINE

Figure 4.13: Machine's block

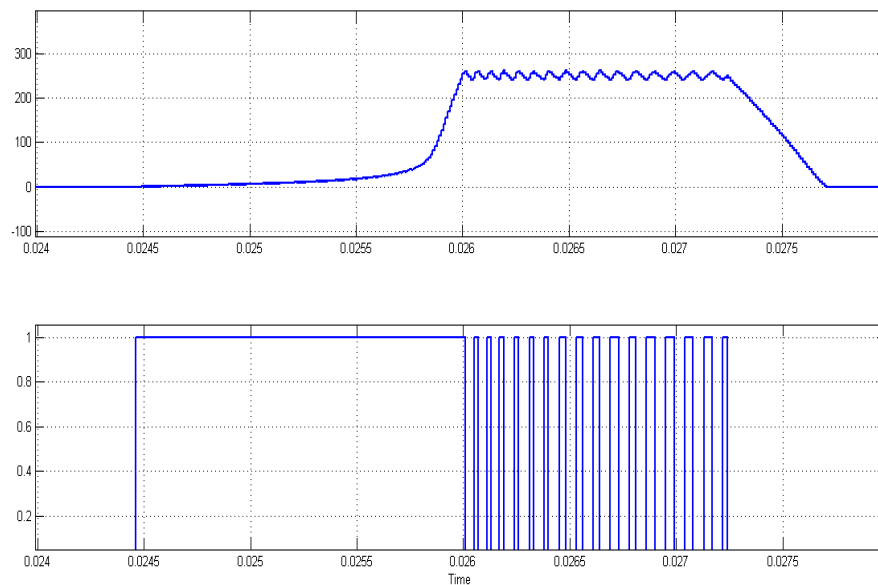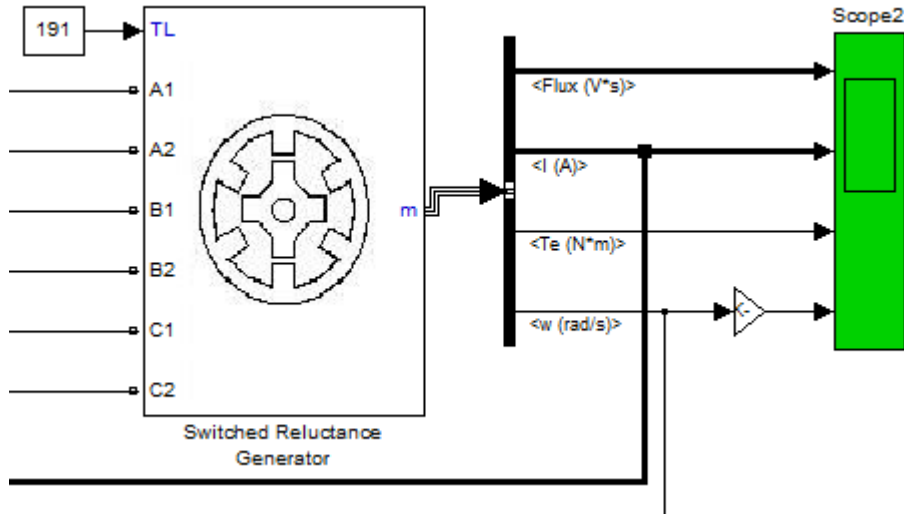Looking under the machine block is possible to understand the circuit representing the machine's equation:
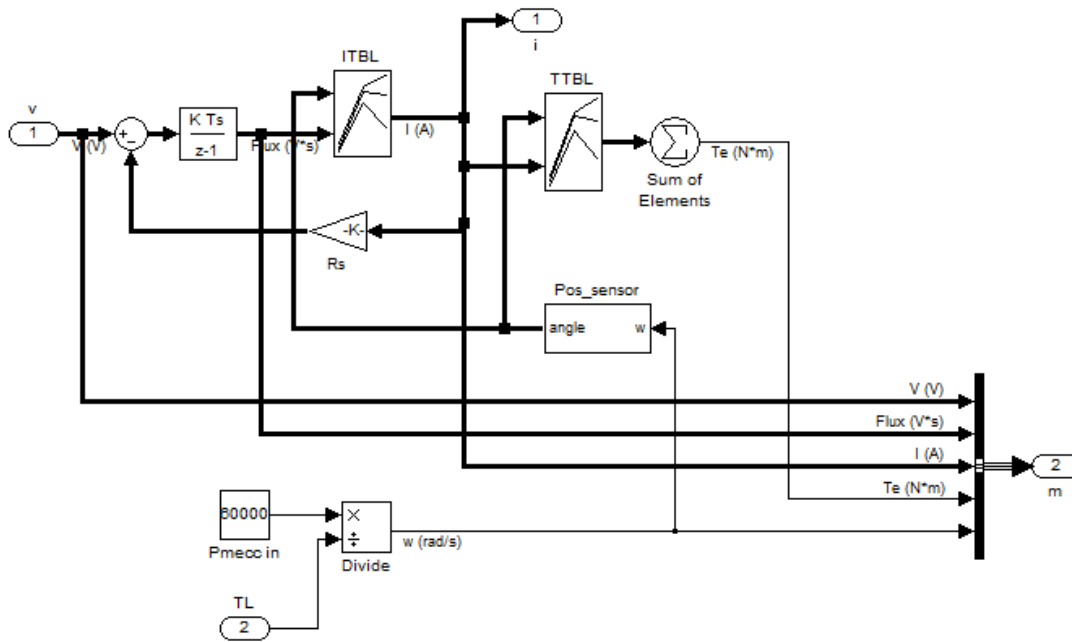

Figure 4.14: basic circuit of SRG

As said the analysis is conduct in steady state conditions assuming a power of 60 [kW] (the machine is a 60kW SRG) and using a constant torque load. Later will be described the model with the integration of the mechanical block.

The input, ω , is scaled to the deg/s unit inside the position sensor block ; afterwards it is integrated in order to find the θ angle.

The circuit equation for a phase is

$$v = Ri + \frac{d\Phi}{dt}$$

The voltage drop Ri is subtracted to v in order to find $d\Phi/dt$. Now with the angular speed ω is possible to calculate the current i with the ITBL. At the end the current is used to calculate the electromagnetic torque T_e and multiplying it per ω is possible to find the output power P_{out} without losses.

4.2 Determination of optimum switching angles

The theta-on and theta-off angles play the major role in deciding whether a SRG develops positive or negative, high or less electromagnetic torque [5]. These angles can be considered function of speed. As explained in the previous chapter the electromagnetic torque is

$$T_{em} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta}$$

so apparently the angular speed ω has no effect on T_{em}, cause the current i is maintained constant with the switching at the reference value and the variation of the inductance respect of theta, $dL(\theta,i)/d\theta$, has every time the same profile, but $d\vartheta = \omega dt$ so it means that there is a relation between them. This can be explained with a sample reasoning. If ω is higher it means that the changing of positive and negative slope of L is faster so the current flows through the phase for less time. When the transistors gates switch on, the current starts to flow through the phase , but its initial value is zero and need time to reach the reference value (250 A in this case) ; but this time is every time the same cause is the duration of the transitory. So if ω is high it means that θ_{on} angle has to be anticipate if the peak of current has to be reach when the negative slope starts. Moreover the current has a transitory time when θ_{off} is reached to come back to zero value when the negative slope is finished. So with high value of ω the theta off angle has to be anticipate (before the end of the negative slope) . This is necessary because if the angle is maintained like in ideal conditions so like if the current pass from 0A to 250A instantaneously , there is still current flowing through the phase during the positive slope and the electromagnetic torque pass from a positive value to a negative value in few time and every cycle. This is translate in less production of power, double side power flow unwanted and magnetic efforts that can damage the machine. After this discussion is now possible to understand how the firing angles can be evaluated. As shown in figure 3.14 and 3.15 there is a reference range of theta-on and theta-off:
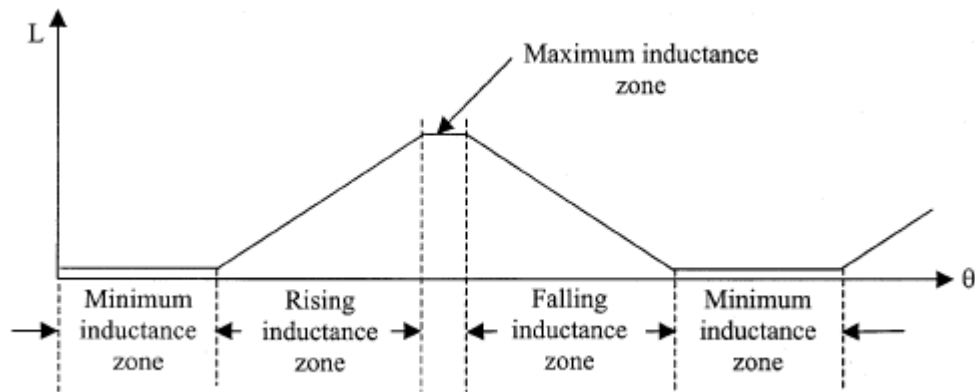
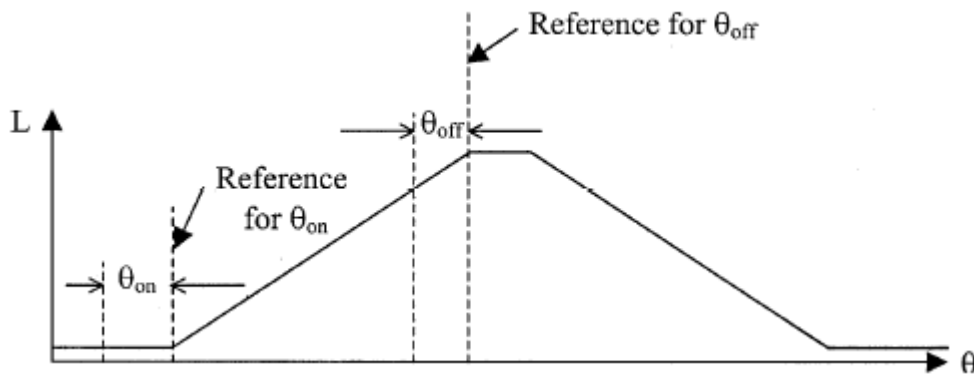**Figure 4.15**: different zones of inductance in one phase

Figure 4.16: Turn-on and turn-off angles in one phase

The effect of changing firing angles is evaluated in terms of different performance indices but depends on the type of control that is wanted. For example if a speed control is the objective the performance indices, as well explained in [5], a potential strategy to be applied consists of the following specifications :

- Time required by the machine to reach within 1% of rated speed;
- Speed overshoot over and above 101% of reference value;
- Speed undershoot under and below 99% of reference value;
- Time required to reach and stay within 1% of rated speed;
- Steady state speed ripple (peak to peak) on full-load;
- Steady state torque ripple (peak to peak) on full load.

Moreover this thesis is initially studied with simple parameters so with constant angular speed ω and this approach is not applicable. A simple evaluation is done, looking the test results with a constant angular speed and choosing the angles that give the maximum output power but without inversion of torque sign. After several simulation the best angles is found in θ_{on}= -30 and θ_{off} = 40. For the *mod block* inside the sensor position that as explained permit to have the same value of theta angles, the

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turn on angle becomes $\theta_{on}= 60$ cause is not possible to have negative value cause the measurement of theta goes from 0 to 90 degrees. To have this combination of angle is necessary to change the logical port in the sensor position from AND to OR:
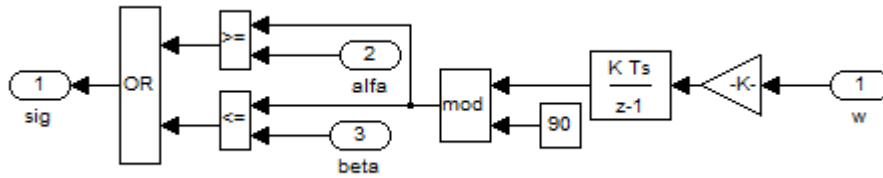

Figure 4.17: Position sensor circuit for optimal firing angles

Now the output of the logical port is TRUE if at least one input is TRUE. It means that when theta is higher or equal than 60 one input is true, the one of alpha, when theta is from zero to 40 the second input becomes true. This block needs to be modify if a control speed is the objective cause every time that alpha condition change from zero to a value lower than beta the AND port is necessary. So the OR port is used when the angle needs to be anticipate from 0 while the AND port is the correct one if the angle value choose is zero or retarded from zero. The next figures show the improvements of the machine trying to find the correct firing angles from the initial situation :
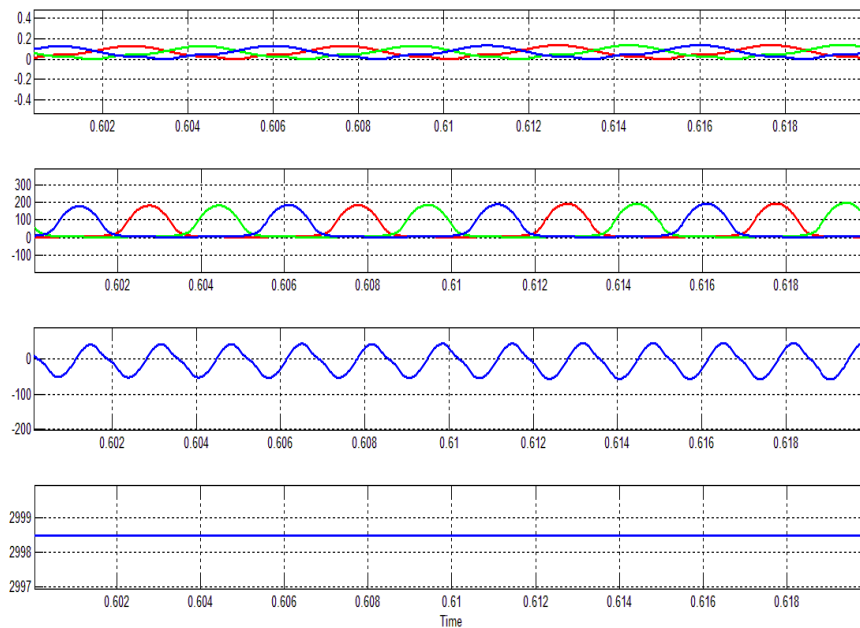
Figure 4.18: Ψ, i, T_{em}, ω profile with $\Delta\theta = 0 \div 45°$

Figure 4.19: $P_{out}(without\ losses)$ with $\Delta\theta = 0 \div 45°$
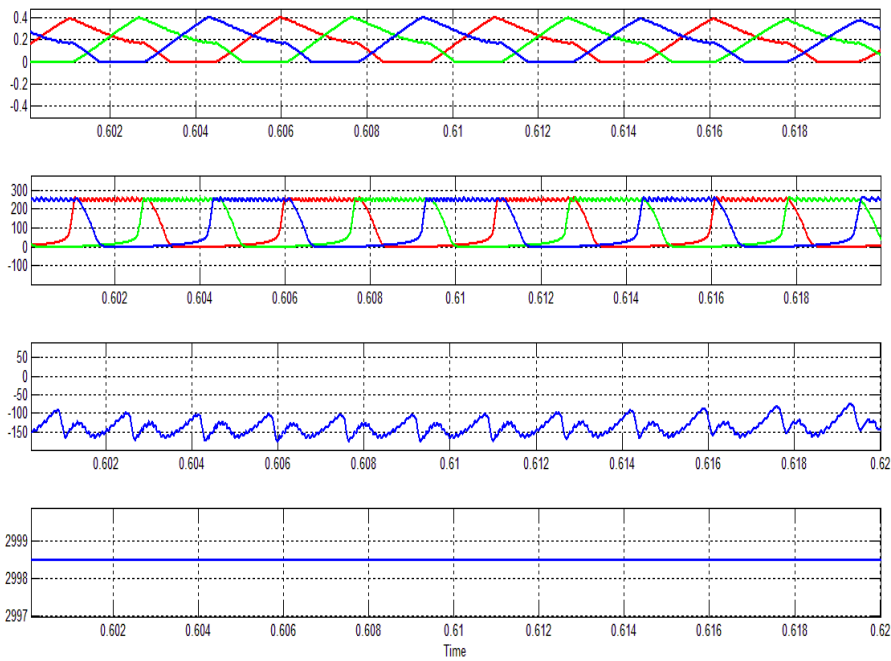
Figure 4.20: Ψ, i, T_{em}, ω profile with $\Delta\theta = -15 \div 45° (75 \div 45°)$
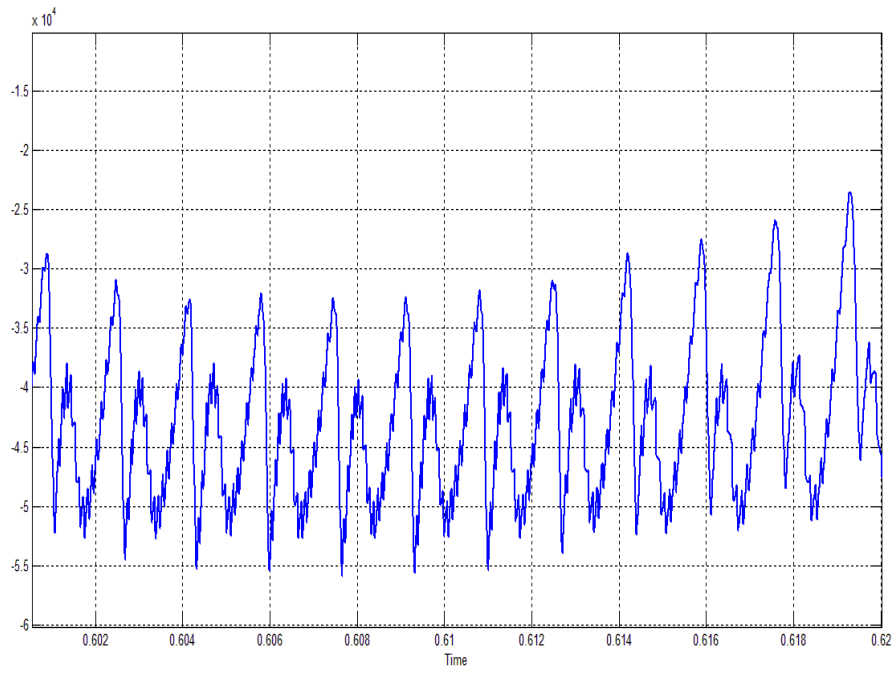
Figure 4.21: $P_{out}(without\ losses)$with $\Delta\theta = -15 \div 45°\ (75 \div 45°)$

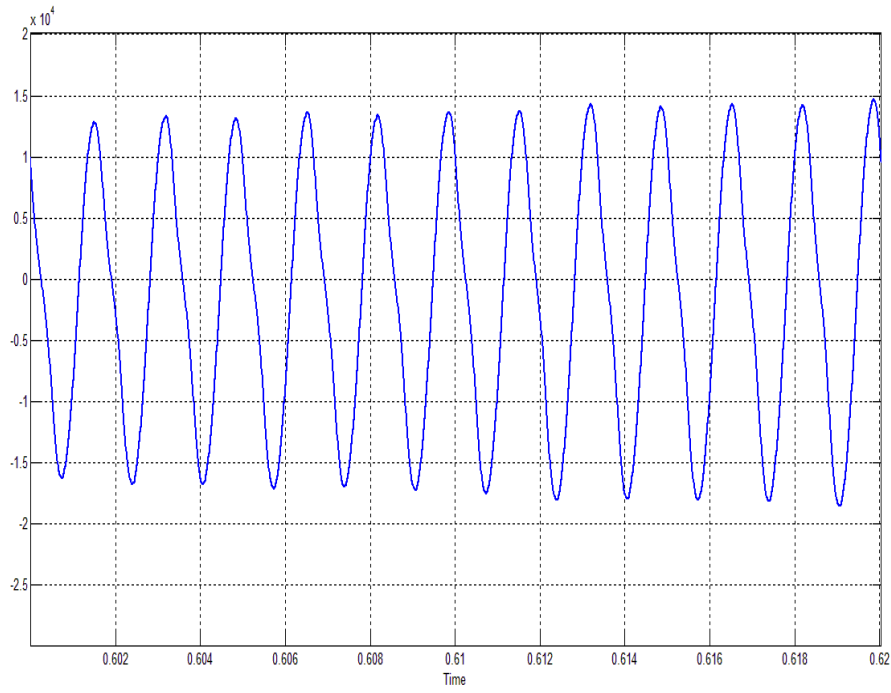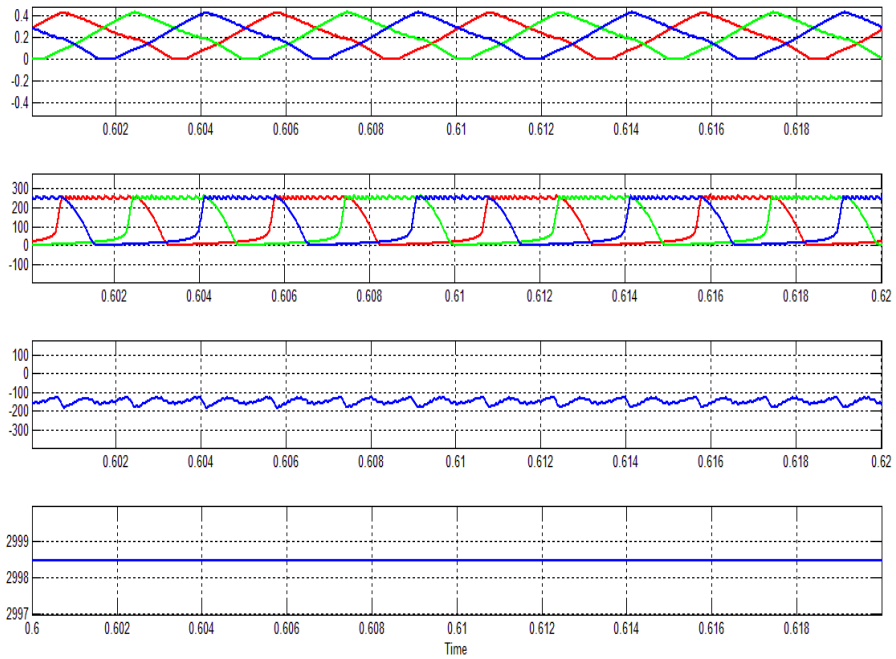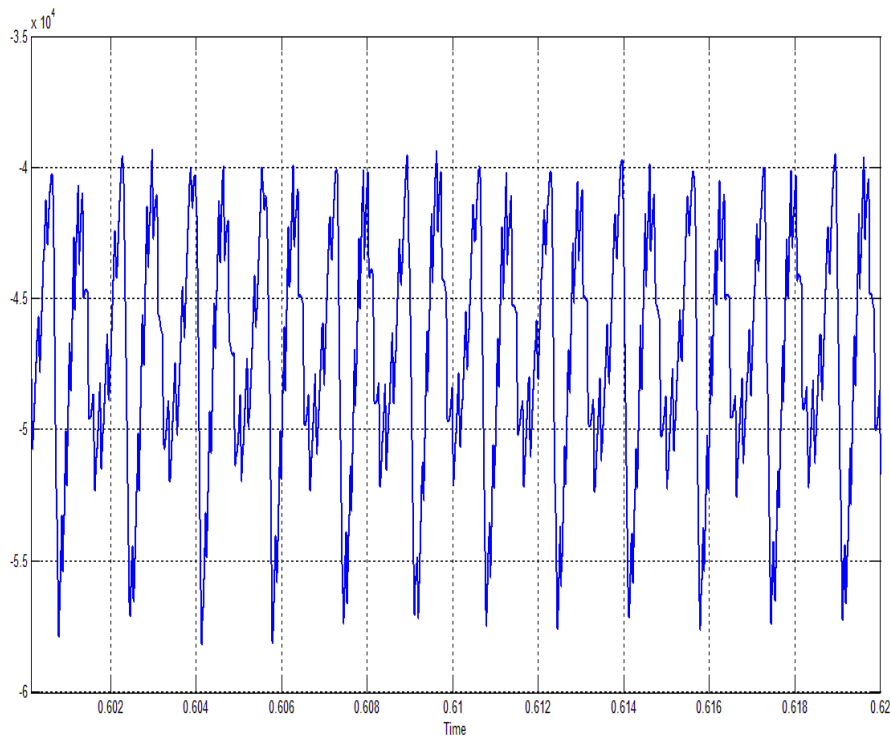**Figure 4.22**: Ψ, i, T_{em}, ω profile with $\Delta\theta = -30 \div 40°\ (60 \div 40°)$

Figure 4.23: $P_{out}(without\ losses)$ with $\Delta\theta = -30 \div 40°\ (60 \div 40°)$

It must remember that the output power shows in these pictures is not the output power that is flowing to the grid but is the electromagnetic output power storage in the air gap before the electric losses.

Simulations start from the initial condition of a firing angle of $\Delta\theta = 0 \div 45°$ where, considering the same period for every simulation, is not in steady state condition yet and it takes a lot of time cause the angles are of an ideal condition that neglect the mechanical closing time of the switches and the time to reach the maximum value. Finding the correct solution is possible to see that the output power increase but also the ripple because of the torque ripple but decrease the delta cause the power is changing at the beginning from 15kW to -15kW, after has a delta of 20kW and with the correct solution delta is 10 kW as shown in figures.

The next table shows the power that can be delivered to the grid by a parametric analysis involving the value of θ_{on} and θ_{off} in order to find the optimum angle for this machine at the constant rated value of rotor speed . Here are reported only the mains combinations that were more close to the solution but several simulation were conducted.

ϑ on [degrees]	ϑ off [degrees]	Pout [kW]
0	40	25
-10 (80)	40	31,2
	45	30
	50	31
-20 (70)	40	37
	45	35,5
	50	30
-25 (65)	40	39
-30 (60)	37	40
	38	40
	40	41
	42	40
	43	40
	45	39
	50	36
-33 (57)	40	40,5
-35 (55)	40	39

So it's possible to see that anticipating the turn-on angle and the turn-off angle is translate in an increase of output power but anticipating too much decrease again the output power and increase also the ripple.

4.3 Grid side

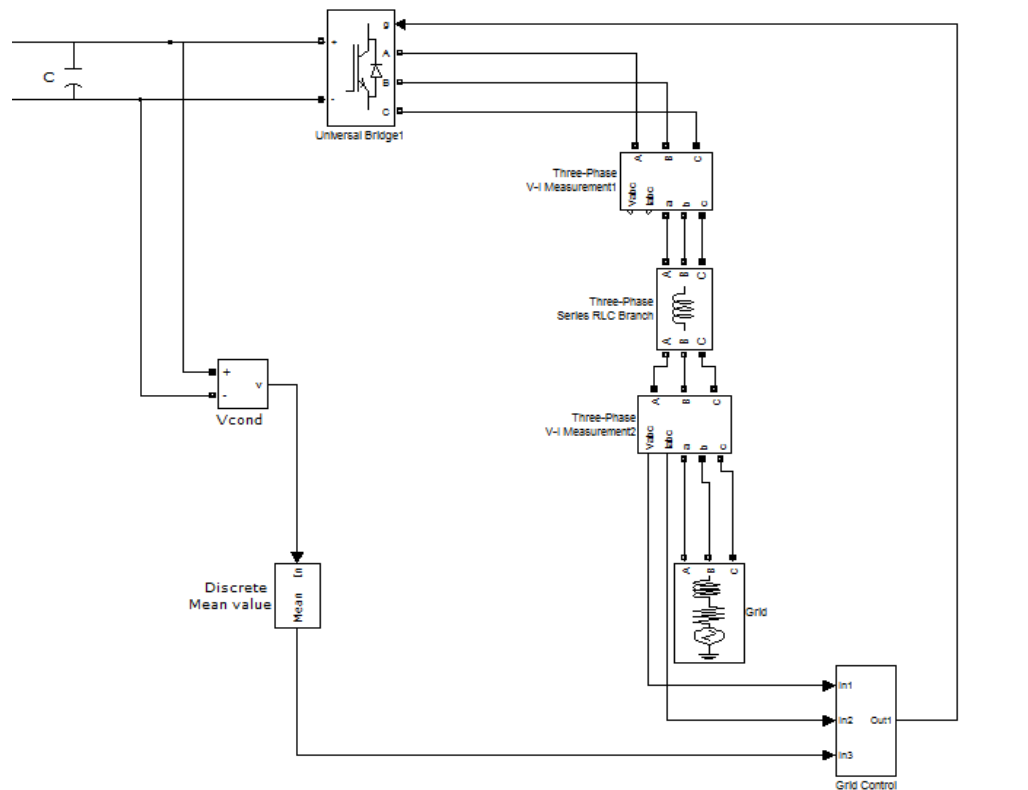In this paragraph is explained the grid side configuration referenced to figure 3.23:

Figure 4.24: Grid side configuration

The capacitor is connected to an inverter that convert the power from DC to AC for the power delivery to the grid. A line is simulate with an inductance L that is connected to the grid block that represents a three-phase voltage source with an inductance and a resistor in series as source impedance cause the grid can always be seen as an inductive load, seeing most of consumers are resistive-inductive. The parameters of the grid are chosen seeing that publication ratings on grid side are similar to ours. Also the power flow to be in the correct direction needs the grid voltage similar but a bit lower than capacitor voltage. The parameters are choose as

$$\boldsymbol{V}_{ph\ to\ ph} = 100\angle0\ [V] \qquad R_g = 0.1\ [m\Omega] \qquad L_g = 0.419\ [mH]$$

Now the objective is to keep the voltage on the capacitor constant at a value of 240V and extract the maximum power.
To evaluate the amount of power that is possible to transfer from the inverter to the grid is necessary to elaborate the equation representing the situation that is shown in figure 3.24:
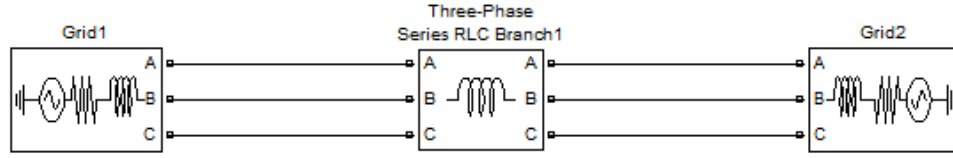
Figure 4.25: Grid side representation

The Grid1 represent the voltage source out of the inverter, the three-phase RLC branch represent the line and the Grid2 the real network. As known:

$$i_g \angle \Phi = \frac{V_i \angle \delta - V_g \angle 0}{X \angle 90}$$

Where:

i. $i_g \angle \Phi$ is the current flowing from the inverter to the grid;

ii. $V_i \angle \delta$ is the inverter voltage;

iii. $V_g \angle 0$ is the grid voltage;

iv. $X \angle 90$ is the line impedance.

And so

$$\overrightarrow{i_g}^* = \frac{V_i \angle (-\delta) - V_g \angle 0}{X \angle (-90)}$$

The apparent power is the sum of the active and reactive power like:

$$S = P + jQ = \overrightarrow{V_g}\, \overrightarrow{i_g}^* = \left(V_g \angle 0\right) \left(\frac{V_i \angle (-\delta) - V_g \angle 0}{X \angle (-90)}\right) = \frac{V_g V_i}{X} \angle (90 - \delta) - \frac{V_g^2}{X} \angle 90$$

$$= \frac{V_g V_i}{X} \left(\cos(90 - \delta) + j \sin(90 - \delta)\right) - \frac{V_g^2}{X} \left(\cos(90) + j \sin(90)\right)$$

$$= \frac{V_g V_i}{X} \sin \delta + j \left(\frac{V_g V_i}{X} \cos \delta - \frac{V_g^2}{X}\right)$$

So at the end the active and reactive power to the grid results:

$$P = \frac{V_g V_i}{X} \sin \delta$$

$$Q = \frac{V_g V_i}{X} \cos \delta - \frac{V_g^2}{X}$$

The module of the voltage out of the inverter is

$$V_i = \frac{V_{DC}}{2\sqrt{2}} \, m \, \sqrt{3}$$

Where m is the modulation index of the PWM and $V_i \; and \; V_g$ the line voltage value.

From a previous model without the connection to the grid but only with a control current source that extracted the maximum current keeping the capacitor voltage at 240[V] is found that the maximum power could be 41[kW]. Based on this result is possible to find the correct value of the modulation index and the voltage phase, $m \; and \; \delta$, in this way:

$$\vec{i_g} = \frac{P/3}{\vec{V_g}} = 236,7\angle 0°[A]$$

Where

$$\vec{V_g} = \frac{V_{g\,ph}\angle 0°}{\sqrt{3}} = 57.735\angle 0°[V]$$

is the grid line voltage. The current phase is imposed at zero degrees in order to have it in phase with the grid voltage to obtain the maximum transfer of active power and the minimum reactive power. Based on this, the inverter line voltage has to be:

$$V_i\angle\delta = V_g\angle 0 + \; i_g X\angle(0 + 90) = 65,647\angle 28,42 \; [V]$$

And from the relation above m will be:

$$m = \frac{V_i * 2 * \sqrt{2}}{V_{DC}} = 0.773$$

With $\delta = 28,42°$, $m = 0.773$, $V_{DC} = 240[V]$, $X = 2\pi f L = 0.132[\Omega]$ results:

$$P = \frac{100 * 113,7}{0.132}\sin 28,42 = 41 \; [kW]$$

$$Q = 0[VAR]$$

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4.3.1 GRID CONTROL

As already said the objective is to maintained the voltage on the capacitor at a constant value of 240 [V] because it becomes the source voltage that have to supply the machine. This mean that when the voltage exceed the reference value of 240[V] is possible to extract more current and so power, when the voltage is lower than the reference value it means that is necessary to extract less current so less power. The control configuration adopted in this thesis is based on a balanced sinusoidal waveforms generator in which modulation index m and phase shift δ are driven through two PI controllers as shown in Figure 3.25
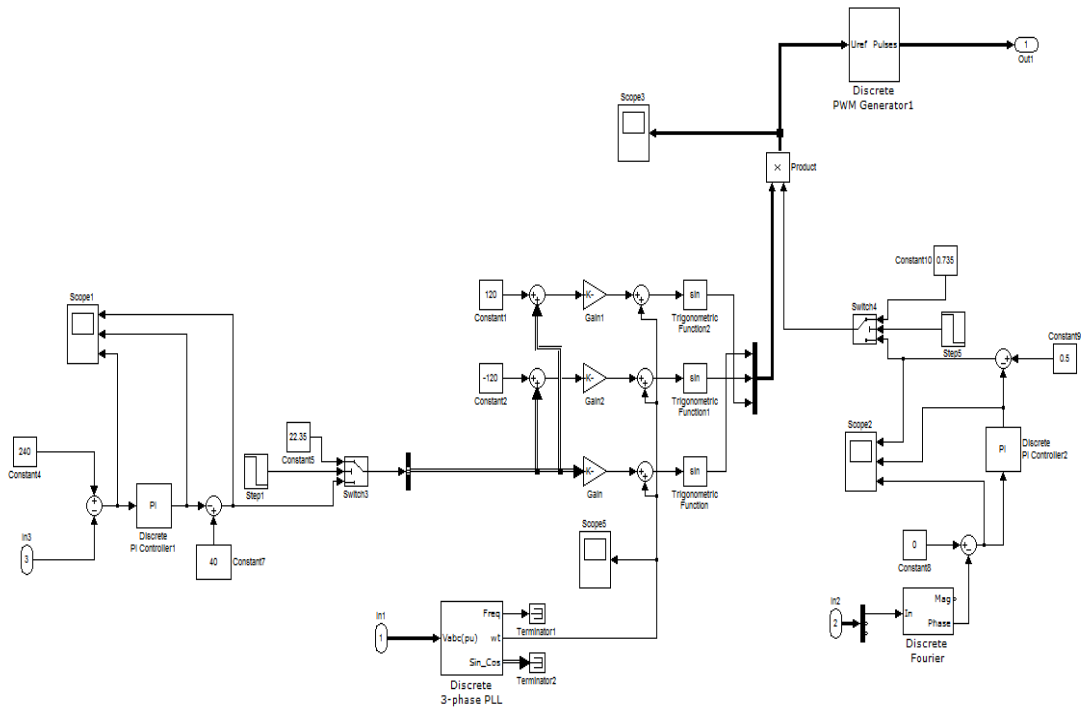

Figure 4.26: grid control

Modulation index follows V_{DC} in different way: if V_{DC} increases it means more power should be extracted from the capacitor so the amplitude of grid current i should increases too. A way to let i grows is to increase voltage drop on grid inductance ,L_g and it can be done increasing V_i through an enlarge value of m . On the other hand, for the Power Factor correction, must be controlled in a way it brings i parallel to V_g that has zero phase so it means that $\Phi \longrightarrow 0°$. This can be done moving the voltage drop $j\,\vec{\imath}\,wL_g$ perpendicular to $\overrightarrow{V_g}$ through an equivalence shift of δ .

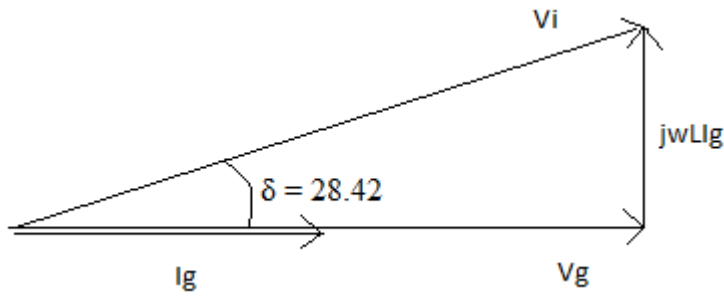At the beginning the situation is what figure 3.26 shows:

Figure 4.27: Initial ideal grid part configuration

As already said the value are

$$V_{i_l} = 65,647 \ [V]$$

$$m = 0.773$$

$$\delta = 28.42$$

$$V_{g_l} = 57.735 \ [V]$$

And so the power delivered to the grid is:

$$P = \frac{V_i V_g}{X} \sin \delta = \frac{113.7 * 100}{0.132} \sin 28.42 = 41 \ [kW]$$

If the voltage on the capacitor increases mean that more power can be extract, but the increase of the voltage on the capacitor increase the angle delta and the new configuration becomes:
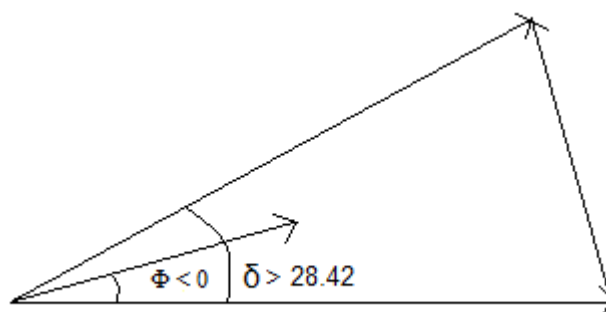

Figure 4.28: Grid side with increase of Vdc

As shown in figure 3.27 an increase of Vdc means that the drop voltage is not perpendicular to V_g anymore(that is constant) and so the current has an angle $\Phi \neq 0$ that cause reactive power $Q \neq 0 \ (< 0)$.
To extract more power is necessary to bring again the current in phase with the grid voltage and to do it an increase of m is necessary.
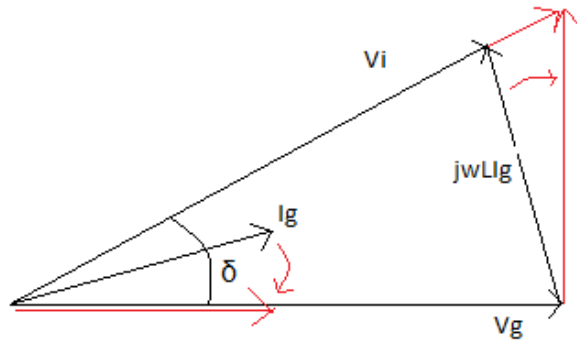
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Figure 4.29: Necessary increase of m

So with a correct increase of m the situation becomes like the beginning but with more active power delivered to the grid.
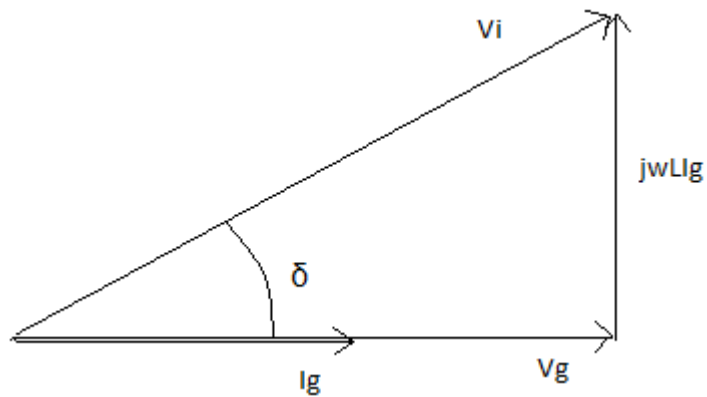
Figure 4.30: new grid side situation with control of m

And the power will be:

$$P = \frac{V_i V_g}{X} \sin \delta > 41 \ [kW]$$

Because V_i now is greater for the increase of m and also the angle so the sine of the angle.

Following the same way is easy to understand the opposite situation: if the voltage on the capacitor is lower than the reference value of 240 [V] means that less power has to be extract and that the angle delta becomes lower so the new configuration becomes:

Figure 4.31: Grid side with decrease of Vdc

Figure 3.30 shows that a decrease of Vdc means that the drop voltage is not perpendicular to V_g anymore(that is constant) and so the current has an angle $\Phi \neq 0$ that cause reactive power $Q \neq 0$ (> 0).

To extract more power is necessary to bring again the current in phase with the grid voltage and to do it a decrease of m is necessary in this case:

Figure 4.32: Necessary decrease of m

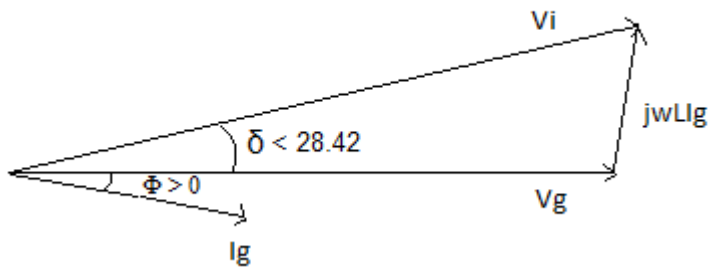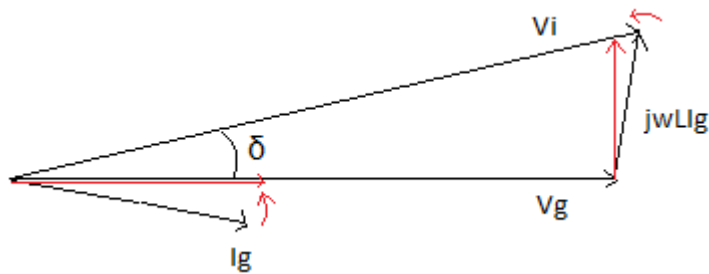With the correct decrease of m the situation becomes like the beginning but with less active power delivered to the grid so the capacitor voltage can increase again at the rated value of 240 [V].
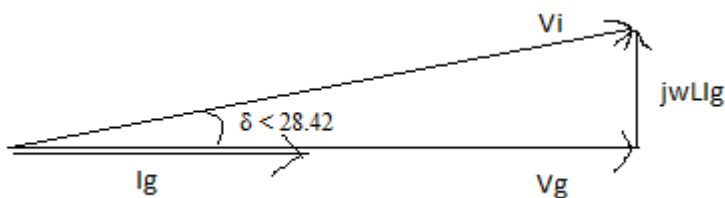

Figure 4.33: New grid side configuration after the control of delta δ < 28.42

The power will be:

$$P = \frac{V_i V_g}{X} \sin \delta < 41 \ [kW]$$

Because V_i now is lower for the decrease of m and also the angle so the sine of the angle.

DELTA CONTROL

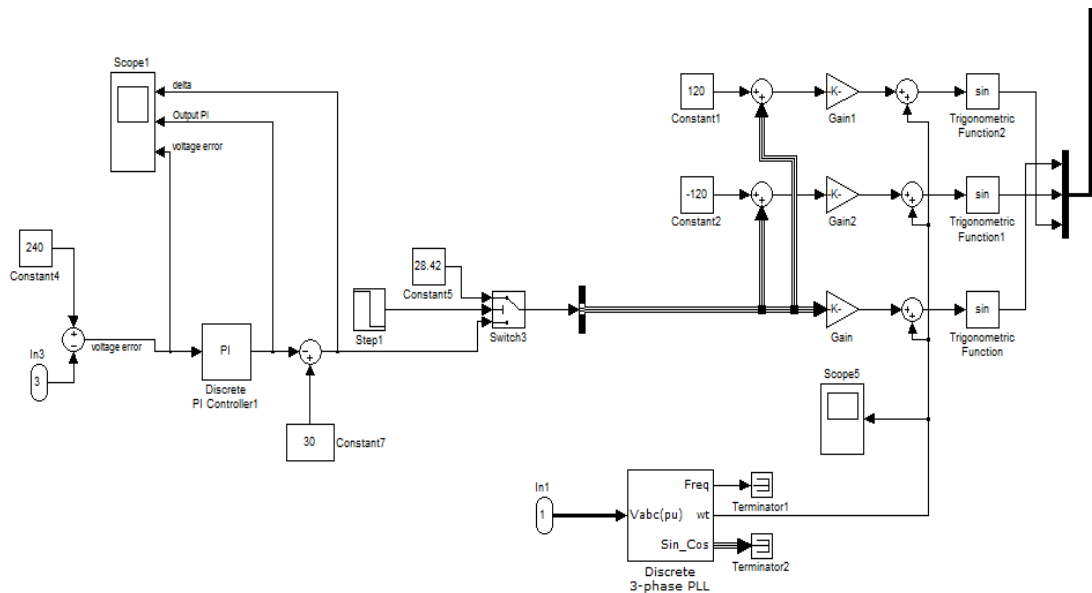Figure 3.33 shows the control part of delta angle δ, while the all control is shown in figure 3.25:

Figure 4.34: Delta control part

In1,In2,In3 are the input from the grid side as shown in figure 3.23.
The first input is the three phase voltage grid measure; the second one is shown later in the control of modulation index m and is the measure of three phase current to the grid; the third input is the measure of the voltage on the capacitor.

The measure of the voltage goes inside a sum block with the reference value of the voltage that wants to maintain constant. The error, that can be positive or negative , is going inside a proportional integrator PI and the output is sum with a constant value fixed at 30 degrees in order to have always a positive value of delta. The switch is at the beginning turn on a constant reference value of delta of 28.42 degrees and after 0.3 seconds is turned off and connected to the control. This is choose because until 0.2 sec the capacitor is charged by the external voltage source and becomes the source after but requires few time to arrive in steady state condition. So the delta output flows inside a three different blocks and after inside gains that transform degrees in radiant. In this way a three phase sinusoidal equilibrate voltage is created and goes inside the final block that is the product with the modulation index. The first input, the three phase voltage grid measurement, flows inside a discrete 3-phase PLL that provide the value of wt that will be sum with delta.
In figure 3.34 are shown the profile of delta, the PI output and the error.
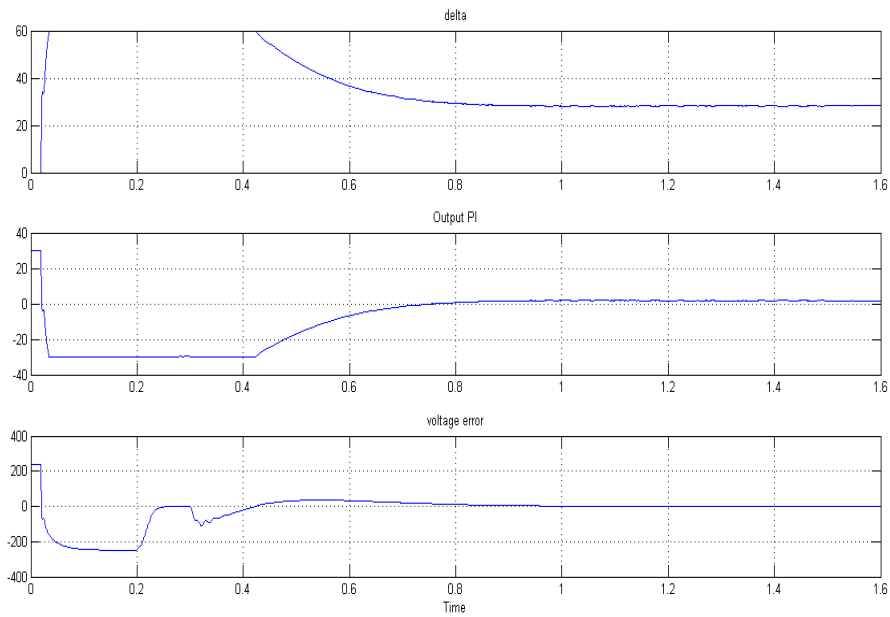
Figure 4.35: Profile of delta, output of PI and the error on the delta control side

MODULATION INDEX CONTROL

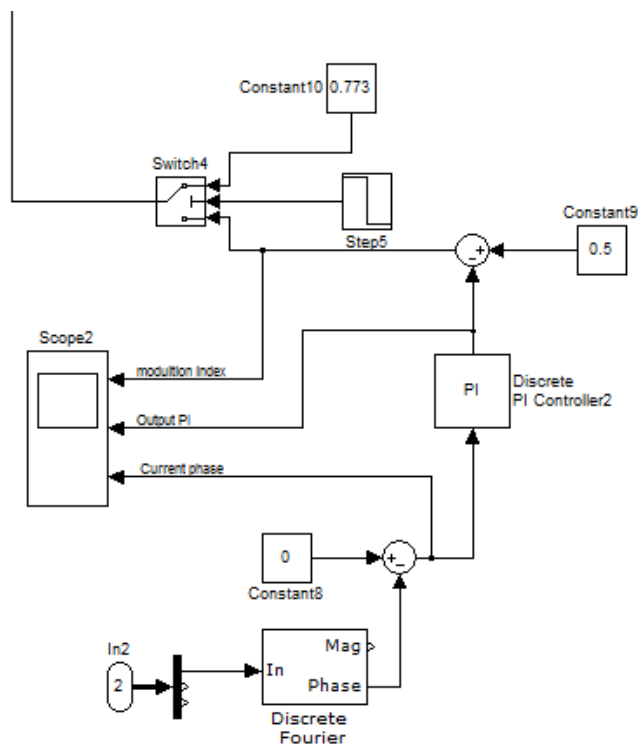Figure 3.35 shows the control part of the modulation index m:

Figure 4.36: Modulation index control part

The second input as already said is the three phase current to the grid measurement. This is demux in order to extract the signal of one phase; this flows inside the discrete Fourier block that provide the output that is the phase of the current Φ. The signal flows inside another PI that gives an output value that, sum with a constant value fixed at 0.5, gives the value of modulation index m. As shown in figure 3.35 also here at the beginning there is a switch on a constant value of 0.735 (ideal condition) until when the external voltage source is disconnected and the capacitor reaches the steady state conditions, at 0.65 sec. Figure 3.36 shows the profile of the modulation index m, the PI output and the phase of the current (with opposite sign):
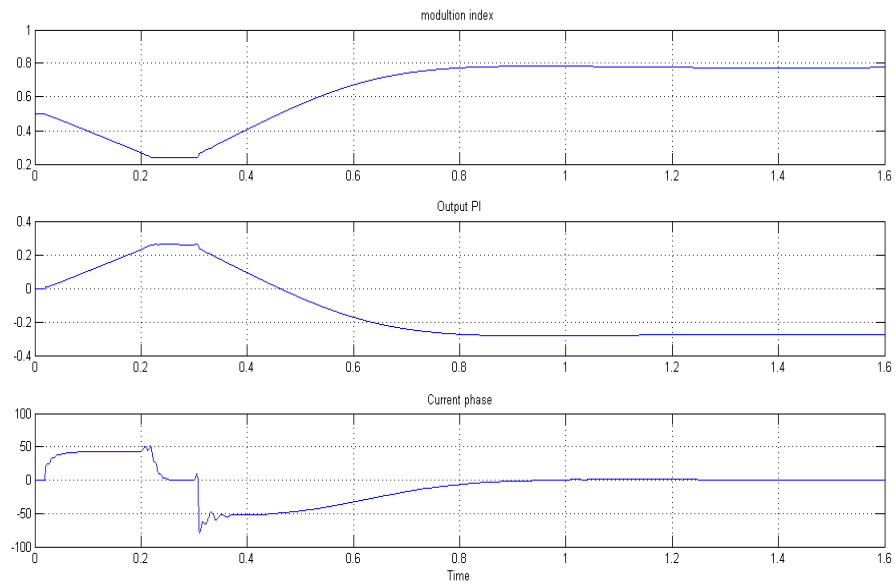

Figure 4.37: Profile of m, PI output, current phase

5 Test results

In this chapter all the simulation results obtained with the SRG model with MATLAB®
SIMULINK® are shown and discuss. All these results are referring to a 6/4 machine which
parameters are now presented.

Machine parameters

6/4, 3 phases, 60 kW Switched Reluctance Machine (6 stator poles,4 rotor poles);

Stator resistance $\qquad$ $R_{stator} = 0.05\ [\Omega]$ $\qquad$;

Inertia $\qquad$ $J = 0.05\ [Kg\ m\ m]$ $\qquad$;

Friction $\qquad$ $B = 0.05\ [N\ m\ s]$ $\qquad$;

Initial speed and position $\qquad$ $\omega_0 = 0\ \left[\frac{rad}{sec}\right];\ \vartheta_0 = 0[rad]$ $\qquad$;

Unaligned inductance $\qquad$ $L_u = 0.67\ [mH]$ $\qquad$;

Aligned inductance $\qquad$ $L_a = 23.6\ [mH]$ $\qquad$;

Saturated aligned inductance $\qquad$ $L_{a_s} = 0.15\ [mH]$ $\qquad$;

Maximum current $\qquad$ $I_{MAX} = 450\ [A]$ $\qquad$;

Maximum flux-linkage $\qquad$ $\Psi_{MAX} = 0.486\ [V\ s]$ $\qquad$.

Torque load $\qquad$ $T_L = 191\ [Nm]$;

Rotor speed $\qquad$ $\omega = 314\ [\frac{rad}{sec}]$;

Reference current $\qquad$ $I^* = 250\ [A]$;

External source voltage $\qquad$ $V_{DC} = 240\ [V]$;

Capacitance $\qquad$ $C = 1000\ [\mu F]$.

In this example a DC supply voltage of 240 V is used. The converter turn-on and turn-off angles are kept constant at -30 (60degrees) deg and 40 deg, respectively [3.3]. The reference current is 250 A and the hysteresis band is chosen as $\mp$10 A.

Current-controlled mode

From stand still up to about 3000 rpm, the motor's emf is low and the current can be regulated to the reference value. In this operation mode, the average value of the developed torque is approximately proportional to the current reference. In addition to the torque ripple due to phase transitions, we note also the torque ripple created by the switching of the hysteresis regulator. This operation mode is also called constant torque operation

Voltage-fed mode

For speeds above 3000 rpm, the motor's emf is high and the phase currents cannot attain the reference value imposed by the current regulators. The converter operation changes naturally to voltage-fed mode in which there is no modulation of the power switches. They remain closed during their active periods and the constant DC supply voltage is continuously applied to the phase windings. This results in linear varying flux waveforms as shown on the scope. In voltage-fed mode, the SRM develops its 'natural' characteristic in which the average value of the developed torque is inversely proportional to the motor speed. Since the hysteresis regulator is inactive in this case, only torque ripple due to phase transitions is present in the torque waveforms.

The analysis is done using the current-controlled mode with a speed constant of 3000 rpm as already said. The simulation graphics show the results with a run time of 1.5 sec that is enough to reach the steady state conditions, considering the detachment of the external source and the connection of the capacitor as new voltage supply.

The next figure shows the complete profile of the main machine parameters: the flux-linkage Ψ, the current through the phases i, the electromagnetic torque T_{em} and the rotor speed that as already said is maintained at a constant value of 314 [rad/sec] that is 3000[rpm] , the machine rated speed.
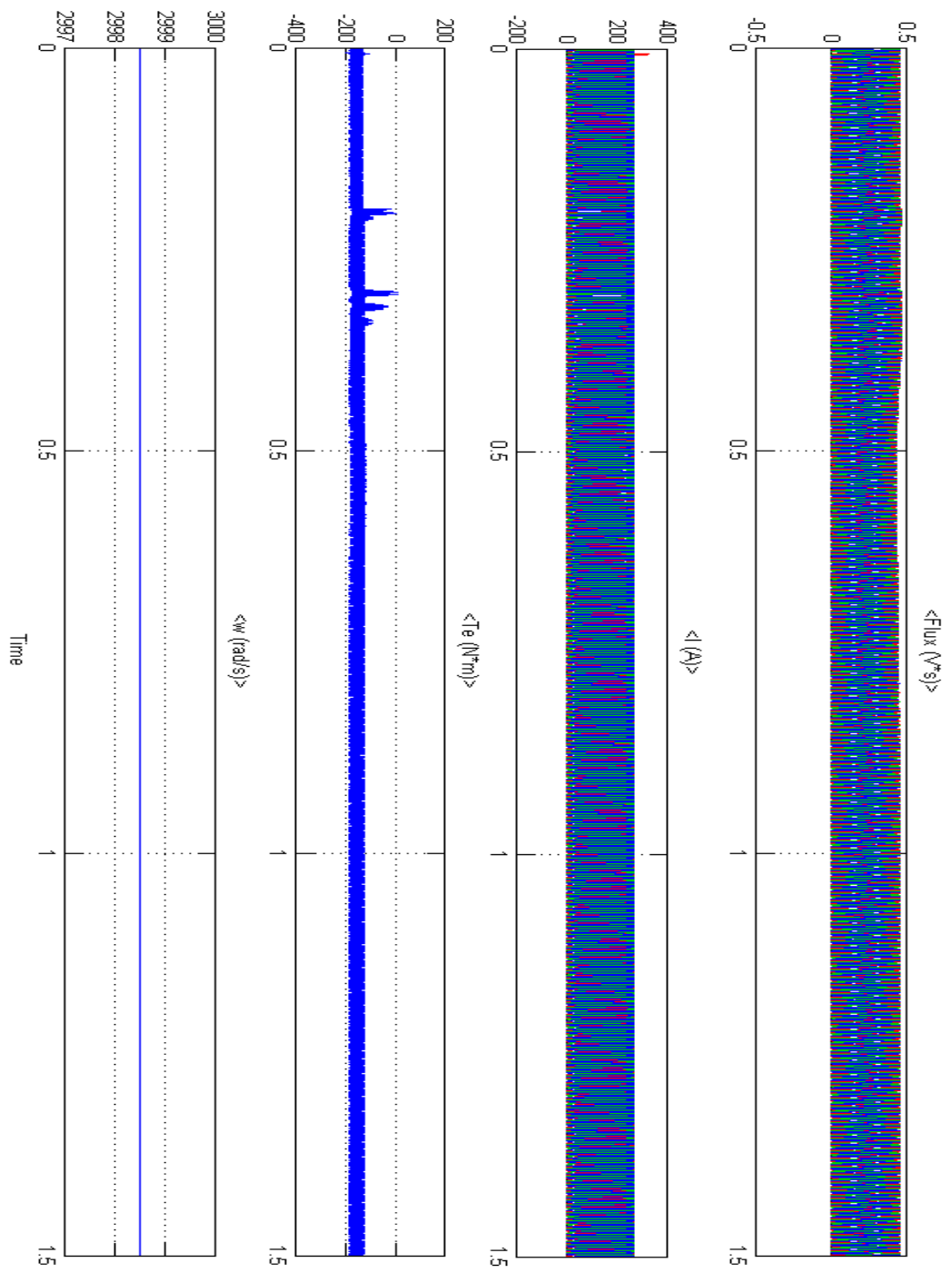
Figure 5.1: SRG drive waveforms

From the profile results is possible to see that there are some critical points.

The first one at 0.2 sec as better shown in figure 5.2 ; there is an increase of the flux linkage and a decrease of the electromagnetic torque for a short time before to reach the same value of the beginning. This fact is caused by the disconnection of the external voltage and the connection of the capacitor like voltage supply; when the capacitor is charged (so when there is the connection) has a voltage value greater than the initial supply of 240 [V] and need time to reach that value with the control voltage. It's possible to see that at the moment of the connection the overlapping of the currents becomes greater for a short time and so the ripple of the electromagnetic torque as well, but in 0.01sec the steady state initial condition are re-established .
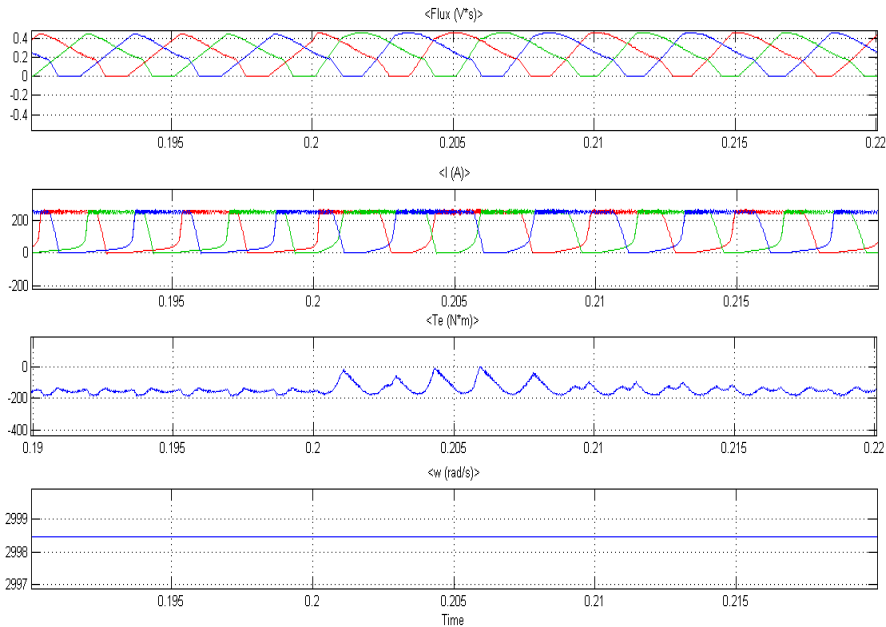

Figure 5.2: SRG drive waveforms at the connection of the capacitor as new voltage source

The second instability, as shown in figure 4.3, starts at 0.3 sec. At this time the grid control is activate so the reference voltage value of the PWM change from an initial ideal value to the real one for the capacitor control voltage. This instability is caused by the fact that the power that is flowing to the grid is at a constant value with 0 reactive power but with an initial open loop so when the control is closed, the cycle need a short time to reach the correct value that the machine had before.
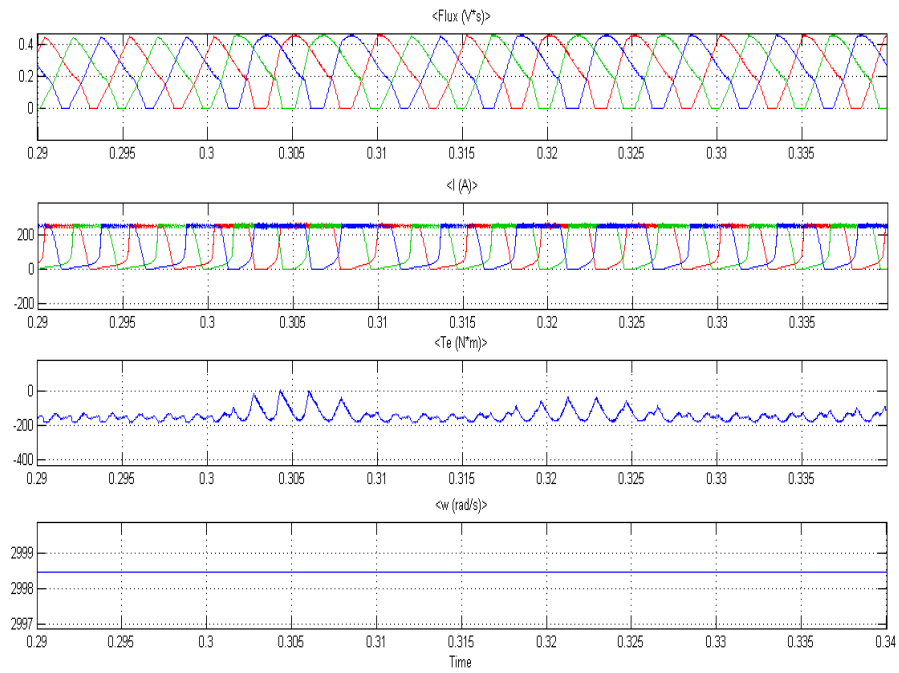
Figure 5.3: instability at the connection of the capacitor voltage control

Figure 4.4 shows the voltage profile on the capacitor;
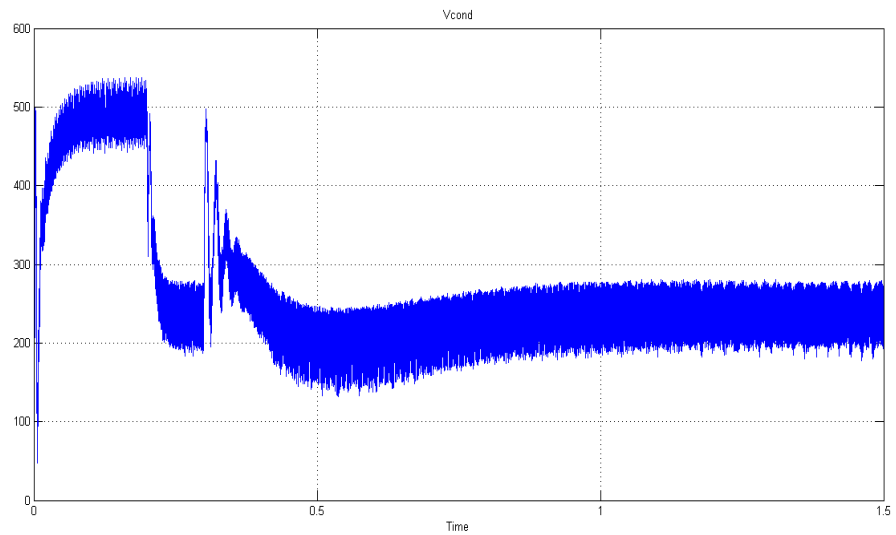

Figure 5.4: capacitor voltage profile

The capacitor is initially charged with the external voltage source until 0.2 sec when is reached its maximum value; at this point the external voltage source is disconnected and the capacitor becomes the supply voltage of the machine so the voltage on it decrease until 240 [V]. The exceed energy is delivered to the grid by the control on the capacitor voltage. At 0.3sec there is the second instability because of the connection of the grid control as already said. After less than one sec the correct value is re-established. Zooming on the profile is possible to see the continue charge and discharge of the capacitor around the reference value of 240 [V].
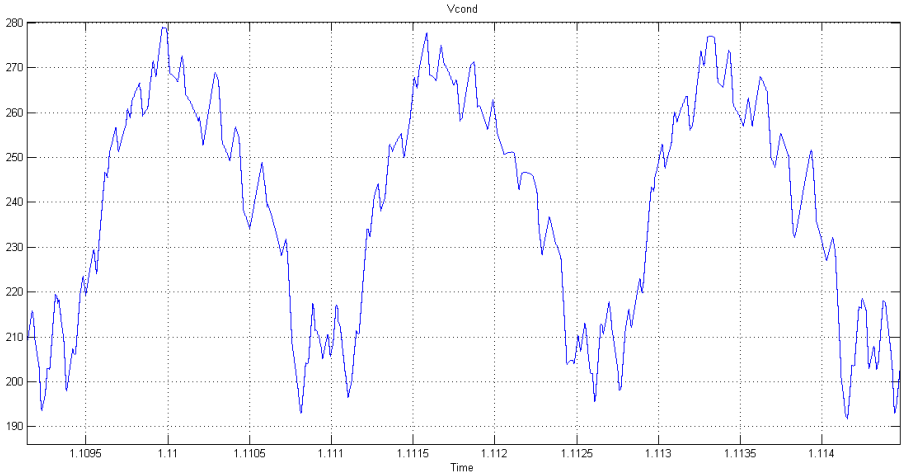

Figure 5.5: Charge and discharge of the capacitor around the reference value

Figure 4.6 shows the profile of PWM phase to phase outside the inverter for one phase. The carrier frequency is fixed at 63*50 [Hz].
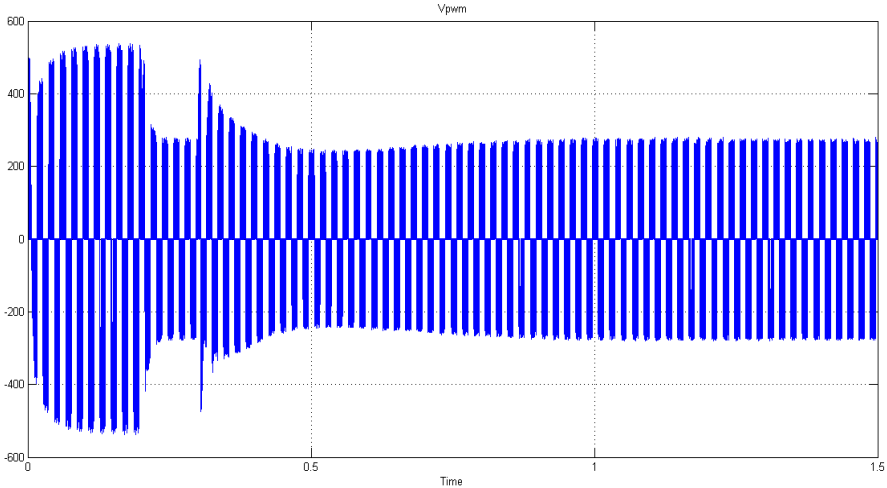

Figure 5.6: PWM profile

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Figure 4.7 shows the three phase V-I measurement outside the inverter (the first profile is the V and the second of I) and after the line inductance, at the grid (the third is the voltage and the fourth the current).
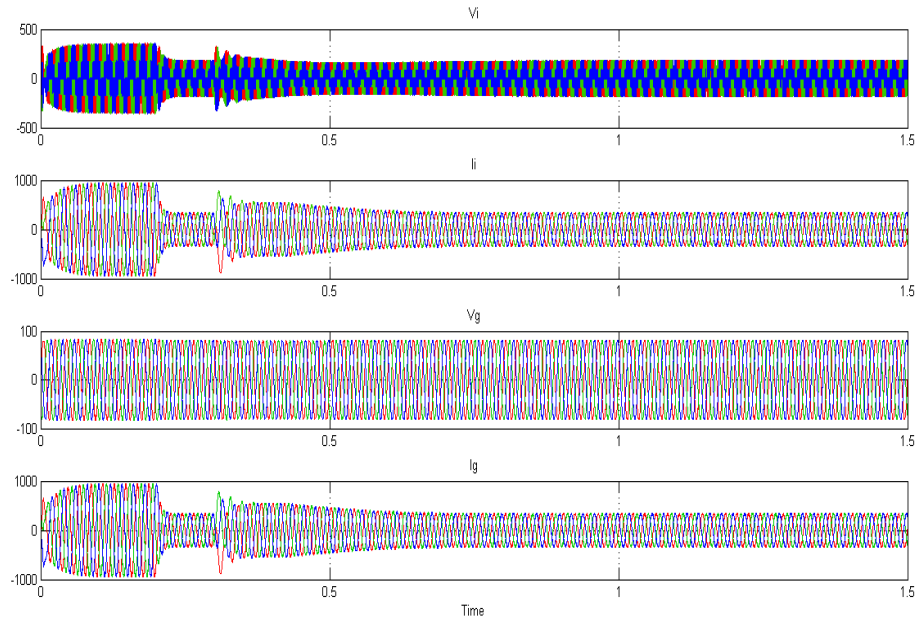

Figure 5.7: Three phase V-I measurement before and after the line.
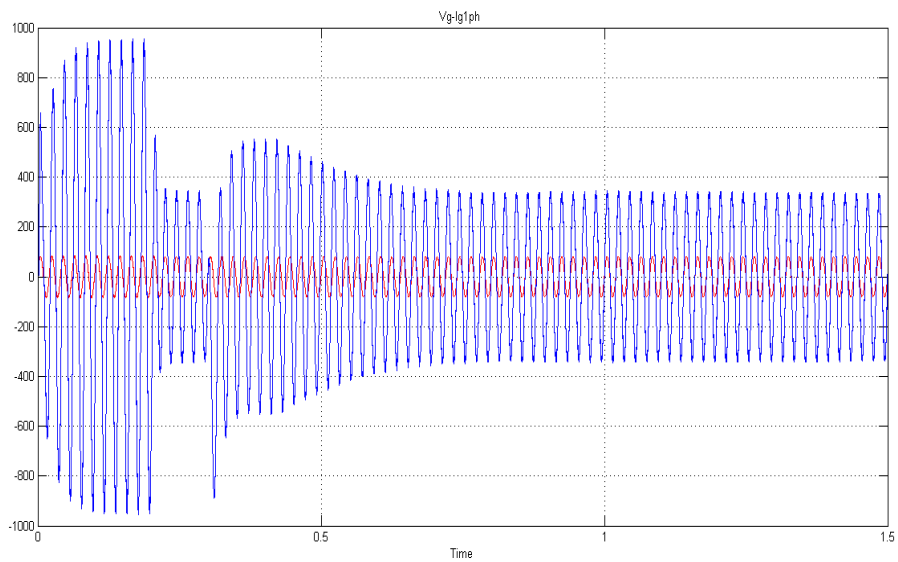

Figure 5.8: V-I grid of one phase

Figure 4.8 shows how the current and the voltage flowing to the grid are maintained in phase (aligned). With a big zoom is easy to see how they pass through zero at the same time.
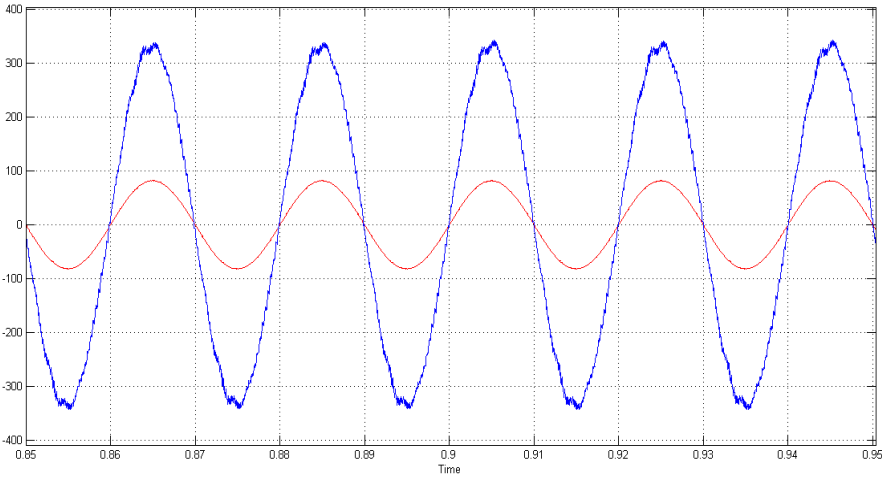
Figure 5.9: V-I grid of one phase zoom

Finally figure 4.10 shows the active and reactive power flow to the grid. After the initial period of capacitor charge, the active power is maintained at a value around 41 [kW] while the reactive power is kept around a zero value by the controller. The copper losses are only on the stator side cause there are no coils on the rotor and in these conditions are $P_J = 3R_s\langle I\rangle = 2.5\ [kW]$
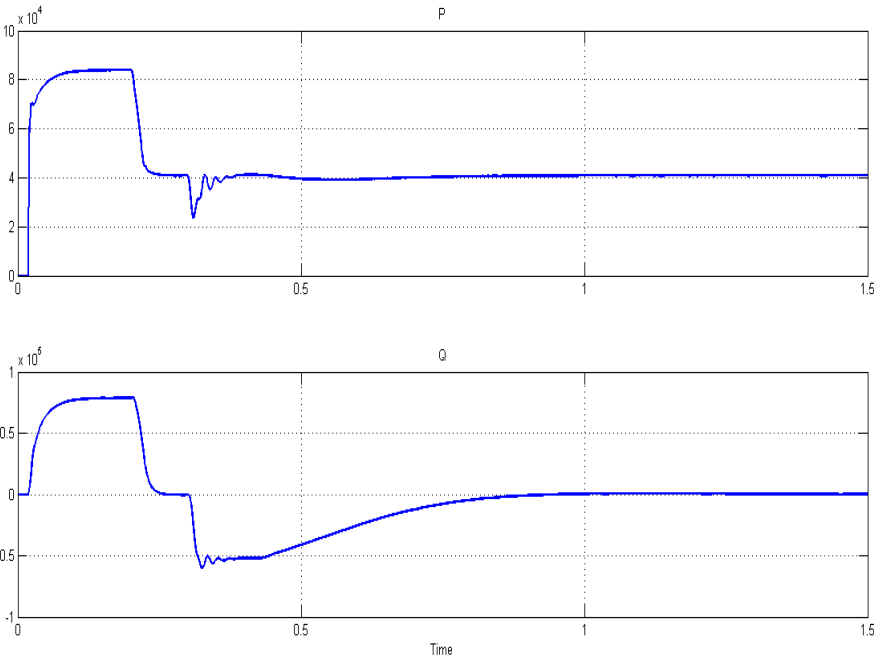
For future works, in order to study the real possible behavior of the machine with different load torque profile, the mechanical block has to be connected again under the machine block, as in figure 6.1, to consider the mechanical equation as shown in figure 6.2:
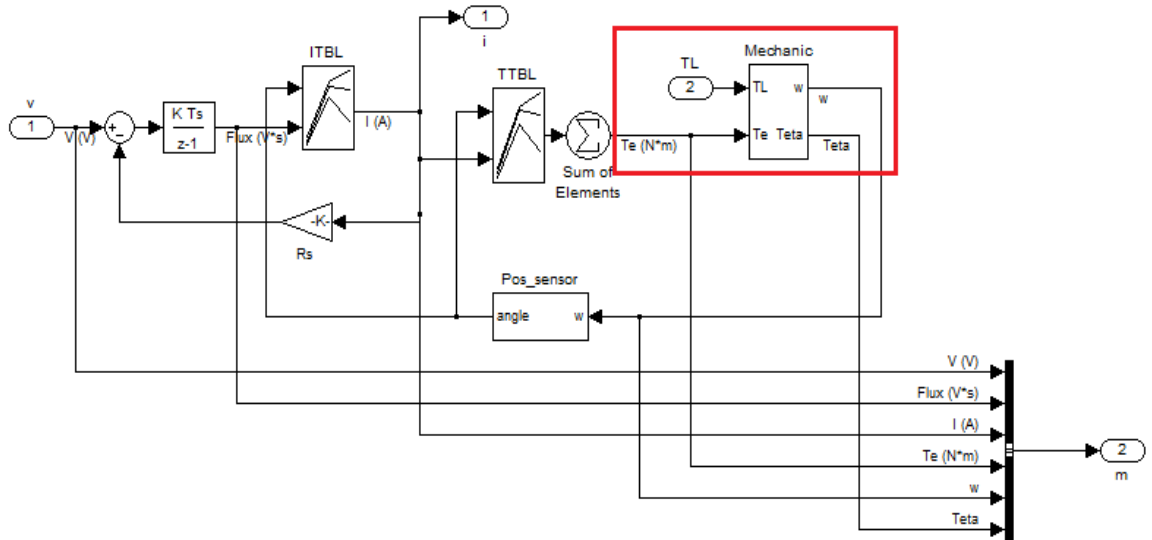
Figure 6.1 : basic circuit of SRG with mechanical block for different torque load
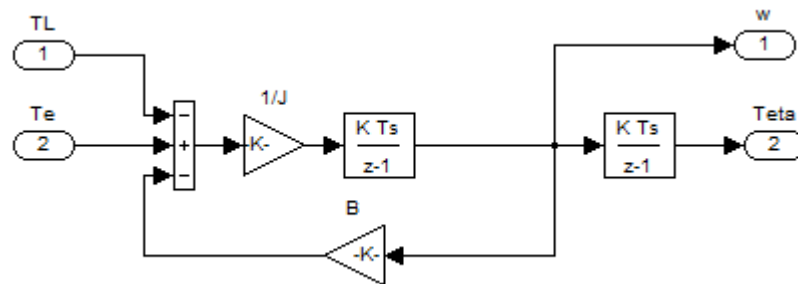
Figure 6.2 : mechanical block

Being the torque equation:

$$T_{em}(i,\vartheta) = T_L + J\frac{d\omega}{dt} + T_f$$

Where:

- T_{em} is the electromagnetic torque ;

- T_L is the load torque ;

- $J\frac{d\omega}{dt}$ is the inertial torque with J inertial momentum ;

- $T_f = B\,\omega$ is the friction torque.

In the generating operation the load torque must be negative ,with the correct firing angles in order to extract power. Another improvement will be the insertion of mechanical characteristic and magnetization curve of a real machine in order to find results for an existing model , where saturation must be included and so conducting analysis in non-linear conditions. Simulations and results are not discussed in this thesis but could be the beginning of the next step.

6 Final considerations and future work

Created the model of the switched reluctance generator SRG that can be adopt different control strategy, it was possible to find an optimal condition for a constant speed in order to provide the maximum amount of power delivered to the grid. The conditions figured out is that for a 60 [kW], 6/4 machine, supplied with an initial Vdc of 240 [V] and a reference current value of 250 [A] with a constant speed of 3000rpm and a firing angles of $\theta_{on} = -30°$ and $\theta_{off} = 40°$ is possible to deliver to the grid an amount of active power of $P = 41\,[kW]$ with a reactive power Q keep at zero value with the grid control as explained in the 4th chapter.

The analysis of the Switched Reluctance Machine done in this thesis is only the beginning of the final objective that is the study of the applicable of it in wave energy. This involve the study of the load torque profile extractable from wave energy and as a variable load causes a variable speed, a digital control on the firing angle must be implemented in order to find for every speed the optimum angle to extract the maximum power in every condition. This could be find basing on the principle of MPPT (Maximum Power Point Track) already used in other applications like photovoltaic. A possible way could be a program that try for every speed all the possible combinations finding a power function (if the maximum power extractable is the objective) that will increase until the reaching of a peak, after that it will starts to decrease so it means that the optimum angles are found and are the combination that provide the peak of the function.

Other characteristics of the machine must be discovered like the extractable power with phase failure for its capacity of working also in this condition for the independent of phases each other , and the study of the same machine with a different number of rotor and stator poles, based on this model. Some doubts about the applicability of SR machine has to be solved about the strong torque ripple that has to be demonstrated being admissible.

The study of this machine and the applicable of it in wave energy should be an interesting and clean way to produce energy in a different way, moreover convenient as already said at the beginning in the 1st chapter compared to the utilization of other electrical machines more expensive.

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Finisce così questo percorso indimenticabile. Questo non sarebbe stato possibile senza tutte le persone che mi hanno accompagnato, quindi questi ringraziamenti vanno a tutti voi.

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Oll-theaghlach mòr

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