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Modeling and Design of Controllers for Switched Reluctance Motor Based on Asymmetrical Γ-Source Inverters

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Abstract – *In this paper a power electronic converter on the basis of asymmetrical Γ-Source inverter has identified to control the speed of switched reluctance motor. In this structure, the converter on the AC side is connected to the three phase power system through three phase three leg inverter while on its DC side supplies a switch reluctance motor throughan impedance network. To have the best control performance (speed control and minimum distortion effects) three loop control system includes impedance network capacitor voltage controller, motor voltage and motor speed controller have been used. Capacitor voltage controller itself contains two sub system include inner current controller in AC side and outer voltage controller to control capacitor voltage. Also speed control unit contains two parts of motor phase current control and external speed controller. Hence totally five control loop have been used to design control system. In order two design aforementioned control systems, dynamic model of asymmetrical Γ-Source inverter has been used for power electronic converters and the time domain dynamic response of motor has been used to design speed controller. The performance of proposed control system has been tested in MATLAB/simulink to prove the performance of the designed control system.*

Keywords: *Power Electronic Converter, Asymmetrical Γ-Source Inverter, Switched Reluctance Motor.*

INTRODUCTION

Switched reluctance motor (SRM) have some benefits such as integrated and strong structure, low loss, long life, robust in case of faults and no need to extra excitation system [1]- [3]. Also for the sake of simple structure and the rotor without winding the cost is low compared with other motors [4]. Because of mentioned benefits this type of machine has lots of application. In [5] SRM is used to control the speed of water pomp. In [6] SRM has been used for rail traction applications. However, proper utilization of this machine needs to consider some effective parameters to its performance such as: nonlinear inductance of windings, dependence of operation to the rotor speed, dependence of back emf generated in windings to the phase current, motor voltage ripple and commutation method [7]. Hence suitable control design to control power electronic converter and motor will affect the operation directly. Therefore, it is necessary to power electronic converter be able to generate constant DC voltage for motor. To this aim various structures are used to design SRM converters [8]. As regards SRM connect to AC system to be controlled, it is necessary to convert the DC voltage to AC one at first and then impose to converter. To generate DC voltage, diode or thyristor base rectifiers can be used. But regarding to the power quality issue and need to have current with power factor close to 1, this type of rectifiers are not recommended. Usage of switching based rectifiers, leads to three phase moderate current with high power factor and low harmonic distortions. Voltage source inverter is the most common converter to convert AC voltage to the DC one and vice versa [9]. In this type of converters, AC to DC conversion is done in controlled manner using high frequency switching; therefore the current with low THD will be absorbed. Yet this converter is the boost converter from AC to DC side and generates higher DC voltage than AC side voltage level. Hence it is necessary to use a DC/DC step down converter. An extra DC/DC converter forces more costs and losses. Z-Source inverter (ZSI) identified in [10] is a single stage buck-boost inverter. In this type of inverters property of buck-boost is obtained by utilizing of impedance network and allocation of shoot through intervals through the inverter switching vectors. Worthy to say that shoot through intervals is not permitted in ordinary VSI and consequence the source to be short circuit and switches damage while in ZSI this action (shoot through interval allocation) is permitted and leads to high reliability. Nevertheless due to single stage structure of this inverter, inverter shoot through duty cycle (D) and modulation index (M) are dependent to each other. So if D increases, for the sake of suitable pulse width modulation algorithm it is necessary to reduce the M that leads high stress on switches. In order to reduce the stress on switches by decreasing D and

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increasing M, various switching control methods have been introduced [11], [12]. In addition to switching based methods, more complicated structures of ZSI have been introduced in which with lower value of D, higher gain is achieved that leads to lower stress on switches. To this end switched inductor ZSI, T-Z- source inverter, trans-Z-source inverter, extended boost ZSI structures have been introduced [13]- [16]. In the last three structures, high frequency transformer is used in impedance network in which increasing turn ratio of transformer make it possible to obtain very high gain despite the low D. nevertheless higher turn ration means higher transformer volume. To eliminate this, asymmetrical Γ-Source inverter has been introduced in [17] in which gain value increases by reducing the turn ratio of transformer. Also in this structure, the ripple of input current to the impedance network is low.

In this paper asymmetrical Γ-Source inverter is used to control SRM voltage and speed. Due to robustness of both SRM and asymmetrical Γ-Source inverter in case of faults, obtained system is a robust one. For suitable control of motor speed, a three loop control system includes impedance network capacitor voltage control, motor voltage control and speed control, have been designed. Impedance network capacitor voltage controller controls the capacitor voltage by regulating inverter current on AC side. By regulating capacitor voltage, motor voltage regulation is possible. With constant controlled voltage on motor terminals, it is possible to design speed controller for motor.

In order to design impedance network capacitor voltage controller and input voltage of impedance network as motor voltage, dynamic model of impedance network has been used. Also with regard to nonlinear and switching based structure of SRM, it is impossible to design the controller by linear methods hence time response of motor in case of a distortion on it is used for its modeling.

This paper has been organized as following: section II introduces power electronic converters structure; section III explains the details of controller design, power electronic converters performance and speed control systems.

The proposed system configuration

The system structure has been shown in Fig. 1. As it can be seen, asymmetrical Γ-Source inverter has been used to control AC side variables and generate the suitable DC voltage for SRM. Existence of switch in impedance network structure, prepares bidirectional power transaction for motor, hence motor is able to operate in generation mode if it is required. In Fig. 1 a 8.6 (i.e. 8 poles for stator an 6 poles for rotor) structure of motor is used. In this configuration asymmetrical Γ-Source inverter converts AC voltage to DC one and regulates input motor voltage simultaneously. With suitable voltage, SRM will be able to generate needed torque by injecting current to the phases of motor. To investigate the proposed system performance, the converter and motor performance will be explained.

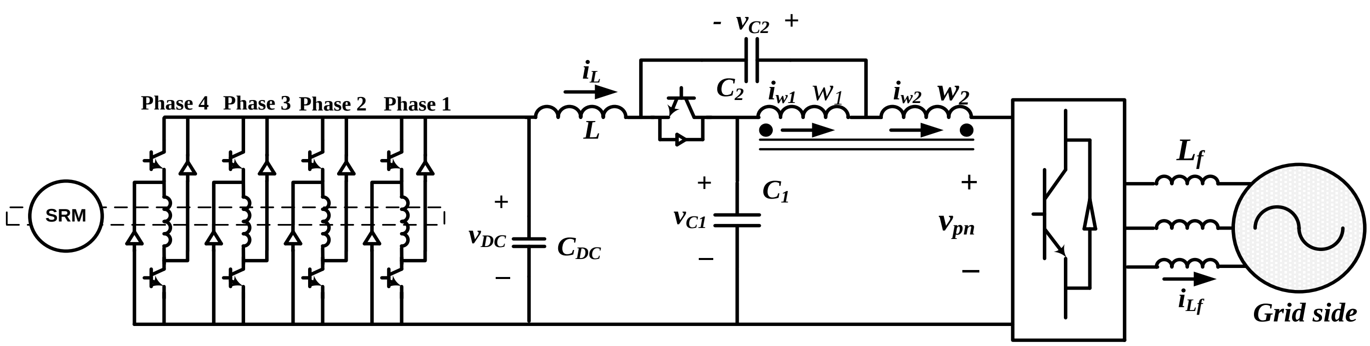


Fig. 1 **-** The proposed converter configuration

A. *Operation of the asymmetrical Γ-Source inverter*

To study operation of this inverter, its equivalent circuit shown in Fig. 2 (a) and 2 (b) which is shoot through and nonshoot through state respectively is used. In this figures load current has been modeled as current source i_o and switch S has been used to model the inverter switching actions. In shoot through state S switch is on and make the output of inverter as short circuit. During shoot through, the energy stored in source and capacitors is released in transformer and inductor. Also diode D is reverse biased. In nonshoot through switch S is off and the load current is supplied by impedance network. Also stored energy in transformer and inductor is discharged in capacitor and leads to DC source voltage increase. In this state diode D is forward biased in impedance network.

In shoot through operation state the voltage relation of transformer, capacitors and inductance are as following:

$$v_{W1} = v_{W2} + V_{C1} \quad (1)$$

$$v_{W2} + V_{C2} + V_{PV} = v_L \quad (2)$$

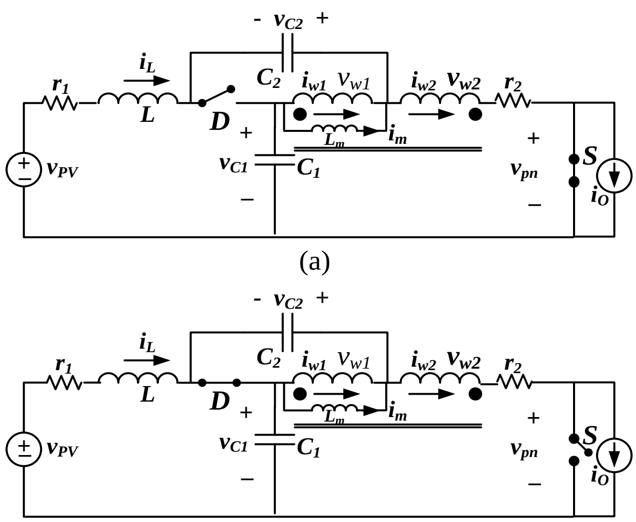
$$v_{W1} = nv_{W2} \qquad (3)$$

In which n is turn ratio of transformer.

In nonshoot through state the relation is as following:

$$V_{C1} + v_L = V_{PV}, V_{C2} + v_{W2} + V_{PV} = v_L + v_{pn} \qquad (4)$$

$$v_{W1} = -V_{C2}, V_{C1} + v_{W1} + v_{pn} \qquad (5)$$



(b)

Fig. 2 - The equivalent circuits for asymmetrical Γ-Source inverter, (a) in shoot through state, (b) in nonshoot through state

Averaging the voltages across the transformer windings and inductor to zero per switching period then results in:

In which D is inverter shoot through duty cycle. Equations (6)-(7) show the asymmetrical Γ-Source inverter in steady state. As it can be seen as (8) is a step up equation. In spite of transformer based Z-source inverters [14]- [16] in which gain increases as turn ratio increases, in this inverter lowering the ratio leads higher voltage gain. Hence the transformer volume is lower in this inverter.

$$V_{C1} = \frac{1-D}{1-(2+\frac{1}{n-1})D} V_{DC} \qquad (6)$$

$$V_{C2} = \frac{nD/(n-1)D}{1-(2+\frac{1}{n-1})D} V_{DC} \qquad (7)$$

$$V_{pn} = \frac{1}{1-(2+\frac{1}{n-1})D} V_{DC} \qquad (8)$$

To obtain the dynamic model of impedance network, state space equations in Fig. 2 (a) and 2 (b) is used. In shoot through operation state equations are:

$$F.\frac{dx}{dt} = A_{st}x + B_{st}u \qquad (9)$$

Where

$$x = \begin{bmatrix} i_L & i_m & v_{C1} & v_{C2} \end{bmatrix}^T, \; u = \begin{bmatrix} i_o \\ v_{DC} \end{bmatrix}$$

$$A_{st} = \begin{bmatrix} -r_1 - (r_2 n^2)/(n-1)^2 & -r_2 n^2/(n-1)^2 & 1/(n-1) & 1 \\ -r_2 n^2/(n-1)^2 & -r_2 n^2/(n-1)^2 & n/(n-1) & 0 \\ -1/(n-1) & -n/(n-1) & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix}$$

$$B_{st} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \text{ and } F = diag\begin{pmatrix} L_1 & L_m & C_1 & C_2 \end{pmatrix}$$

State equation in Fig. 2 (b) is as:

$$F.\frac{dx}{dt} = A_{nst}x + B_{nst}u \qquad (10)$$

Where

$$A_{nst} = \begin{bmatrix} -r_1 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B_{nst} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ -1 & 0 \\ (1-n)/n & 0 \end{bmatrix}$$

Average state equation of impedance network is:

$$F.\frac{dx}{dt} = Ax + Bu, \; y = Cx \qquad (11)$$

Where

$$A = D.A_{st} + (1-D).A_{nst}$$

$$B = D.B_{st} + (1-D).B_{nst} \qquad (12)$$

$$y = \begin{bmatrix} v_{C1} \end{bmatrix}$$
$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}$$

Considering small signal differences in (12) around a given operating point, D differences around operating point $(\hat{d})$ is also an input and leads to differences in *B* and *u* matrices.

Where

$$F.\frac{dx}{dt} = Ax + B'u', \ y = Cx \qquad (13)$$

Where

$$B' = \begin{bmatrix} 0 & 1 & B_{13} \\ 0 & 0 & B_{23} \\ -(1-D) & 0 & B_{33} \\ (1-D)(1-n)/n & 0 & B_{43} \end{bmatrix}$$

$$B_{13} = \frac{-r_2 n^2}{(n-1)^2} I_L - \frac{r_2 n^2}{(n-1)^2} I_m + \frac{nV_{C1}}{(n-1)} + V_{C2}$$

$$B_{23} = B_{13}$$

$$B_{33} = -\frac{n}{(n-1)} I_L - \frac{n}{(n-1)} I_m + I_o$$

$$B_{43} = -I_L - I_m + \frac{(n-1)}{n} I_o$$

$$u' = \begin{bmatrix} \hat{i}_o \\ \hat{v}_{DC} \\ \hat{d} \end{bmatrix}$$

In which I_m , I_L , I_o , V_{c1} and V_{c2} are, magnetizing current, inductance L current, output current, voltage of capacitor C_1 and C_2 in a specific operating point.

According to (13), the system model for design of controllers is as:

$$G_{\hat{i}_o}^{\hat{v}_{C1}} = \frac{\hat{v}_{C1}}{\hat{i}_o} = [0\ 0\ 1\ 0].(FsI - A)^{-1} B' [1\ 0\ 0]^T \qquad (14)$$

$$G_{\hat{d}}^{\hat{i}_L} = \frac{\hat{i}_L}{\hat{d}} = [1\ 0\ 0\ 0].(FsI - A)^{-1} B' [0\ 0\ 1]^T \qquad (15)$$

B. Operation of SRM: In this section the process of mechanical energy conversion to the electrical through SRM is studied. In the SRM when the stator phase exited, leads to magnetic field generation. In the electromagnetic system, torque will be generated in the direction to reduce the reluctance and consequently increase the inductance.

Neglecting the saturation, generated torque in the excited phase of rotor is calculated by (16) bellow.

$$T = (\sum_{i=1}^{N} \frac{1}{2} i_i^2 \frac{\partial L(\theta_r, i_i)}{\partial \theta_r}).\omega_r \qquad (16)$$

In which, T is the shaft torque, ω_r is the rotor angular speed, i_i is i_{th} phase current, $L(\theta_r, i_i)$ is winding inductance in θ_r angular position of rotor and i_i current and N is the number of phases.

Inductance-angular position of rotor curve in the specific current is depicted in Fig. 3. In the motor operation state, it is clear that torque in (16) should be positive. Hence i_{th} phase should be excited in the moments that $\frac{\partial L(\theta_r, i_i)}{\partial \theta_r} > 0$. So at the moment that the poles of rotor and stator are being aliened the corresponding phase should be excited.

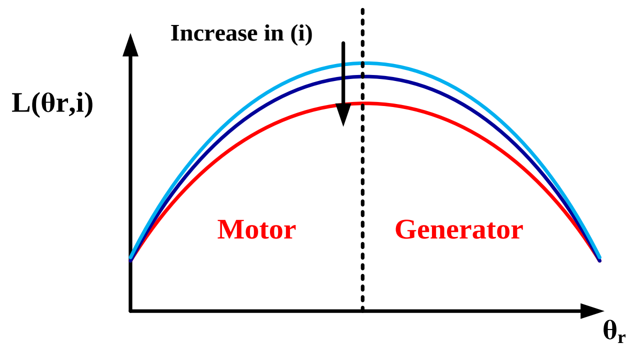


Fig. 3 - Winding inductance of the SRM

Assuming the V_{DC} generated by converter and imposed to the motor, the voltage equations are:

$$v_{DC} = Ri_i + L(\theta_r, i_i).\frac{di_i}{dt} + e(i, \omega_r) \qquad (17)$$

$$e(i, \omega_r) = \frac{\partial L(\theta_r, i_i)}{\partial \theta_r}.\omega_r.i_i \qquad (18)$$

Regarding (16), to increase the generated torque it is necessary to increase the phase current at the suitable moment. Regarding (17), to increase the current, inverter, input voltage should be increased and vice versa. To this aim, phase currents are controlled by controlling switching of SRM converter. In order to increase the current of winding, both upper and lower corresponding phase switches is turned on simultaneously. Also for phase current reduction, two switches are turned off simultaneously. In this condition the phase current leads to diodes in excited phase being conducted and impose– v_{DC} across the motor phases that leads to current reduction. This characteristic can be used to control the phase current by hysteresis method. In this method phase current is compared with its reference value; when the current is lower than its reference the switches is turned on and when the current is higher than the reference value the switches is turned off. In this way the phase current always remains around the reference value. In order to hysteresis algorithm work correctly, is as (19):

$$v_{DC} > \frac{\partial L(\theta_r, i_i)}{\partial \theta_r}.\omega_r.i_i \quad (19)$$

So the V_{DC} should be upper than the specific value. To this end V_{DC} is considered for the maximum value of $\omega_r.i_i$.

Proposed control system

The structure of introduced control system is depicted in Fig.4. In this structure 3 individual control system to control impedance network, voltage control and SRM speed control has been used. In this control structure, by regulating impedance network capacitor voltage, possibility of voltage controller for motor is obtained. In order to control voltage of motor it is necessary to design the controller for capacitor voltage with higher band width compared with motor voltage controller. Designing the motor voltage controller make it possible to design current and speed controller.

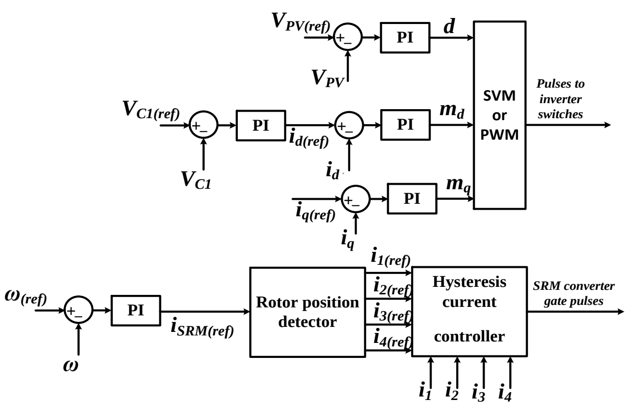


Fig. 4 - The control system architecture

A. Capacitor voltage controller: The structure of capacitor voltage controller has been illustrated in Fig. 4.

Considering network voltage phase as reference phase, active power is the coefficient of direct component of current (i_d) and the corresponding reactive power is related to quadratic component of current (i_q). In order to control the voltage of capacitor located in impedance network it is necessary to specify the i_d such that all active power needed for motor supplied through network. Hence if the capacitor voltage exceeds the reference value, controller should increase the i_d to recover the voltage. Therefore the capacitor controller coefficient should be negative. Regarding in the structure of capacitor voltage, AC current controller is the inner control loop it is necessary to design the inner current controller at first. Note that the network voltage is the three phase balanced voltage, it is possible to use the controller in synchronous reference frame. Considering listed parameters in Table. I, inner AC current controller is designed with 1 kHz bandwidth in which K_{pi}= 10.5 and K_{Ii}= 16000. After designing inner AC current controller it is possible to design the voltage controller with lower band width compared with AC current controller for capacitor "1". To this end impedance network model depicted in Fig. 5 has been used. In this figure value of g relates the value of i_d to i_o in impedance network. In figure 5, the system model obtained from (15) is used to design the controller. Note that due to high band width of interior current controller compared to capacitor voltage controller; it is assumed that reference current is equal to real current. Also to eliminate the transferred reactive power, the value of i_q reference is zero. Using system model shown in Fig. 5, and system parameters listed in Table 1 and choosing K_{PC}= 0.1 and K_{IC}= 20, capacitor voltage controller will be designed with 100 Hz band width.

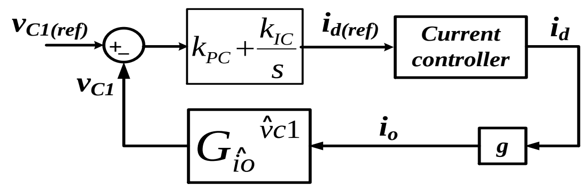


Fig. 5. Capacitor voltage controller

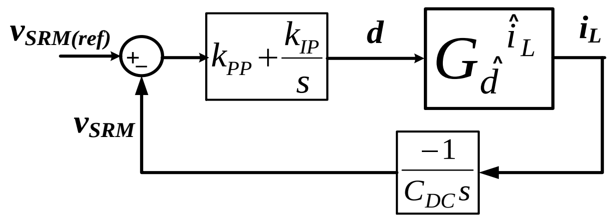


Fig. 6 - SRM voltage controller model

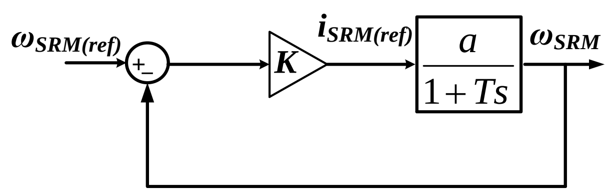


Fig. 7 - The motor model identifier system

Table 1: System Parameters

Parameters	Values
C1	600µF
C2	600µF
L	2mH
Lm	400µH
r1	0.1Ω
r2	0.2Ω
Lf	1.8mH
Cf	45µF
rf	0.1Ω

B. SRM voltage controller: In order to current controller and speed controller correctly control their variables in SRM control systems, V_{DC} should be controlled. To do this coefficient D is used to control motor voltage. As the correct control action of motor voltage is dependent to correct control action of capacitor voltage, it is necessary to band width of motor voltage controller be lower than capacitor C_2 controller. Motor voltage controller uses the D to regulate the voltage to the reference value. Assuming the voltage of C_1 is regulated exactly on its reference value, regarding (6) increasing D leads to reduction of V_{DC} and vice versa. To design the motor voltage control, system model depicted in Fig. 6 has been used. In this figure the transfer function extracted from (15) has been used. Also in this figure capacitive impedance of C_{DC} is used to transfer i_L to v_{DC}. Choosing K_{PD}= 0.0001 and K_{ID}= 0.03, the voltage control system will be designed with 25Hz band width.

C. Motor speed controller: The speed control system diagram is shown in Fig. 4. In this structure an interior current control loop has been used to control to regulate the current and torque. In introduced control system, hysteresis controller has been used to control the phases current. In order to design speed control, it is needed to identify the dynamic response of motor to the disturbance. To this end, the close loop control system shown in Fig.7 is used. In this figure the value of coefficient (K) is chosen on a way that system is stable. Considering first order model of system with the transfer function (20), the values of (T) and (a) should be identified. So by imposing a disturbance to the current by changing speed reference value and observing the system response, (T) and (a) will be determined.

$$G_{SRM} = \frac{\omega_{ref}}{i_{SRM(ref)}} = \frac{a}{1+Ts} \quad (20)$$

Choosing k= 1 and changing the $\omega_{SRM(ref)}$ suddenly from 100(Rad/s) to 150 (Rad/s), the dynamic response of the system is shown in Fig. 8. As can be seen, the system time constant is about 0.14s. Also, the closed loop system gain is as $\Delta\omega_{SRM}/\Delta\omega_{SRM(ref)}$ which is 0.56. The closed loop system time constant (τ) and gain (α) can be obtained by (21). According to (21) and considering τ= 0.14s and α= 0.56, the values of (T) and (a) can be calculated as 0.18s and 1.27. With respect to the calculated system model, and choosing K_{Pm}= 2 and K_{Im}= 1for motor speed controller, the bandwidth of 2Hz for motor speed controller can be obtained.

$$\begin{cases} \dfrac{ka}{1+ka} = \alpha \\ \dfrac{T}{ka} = \tau \end{cases} \quad (21)$$

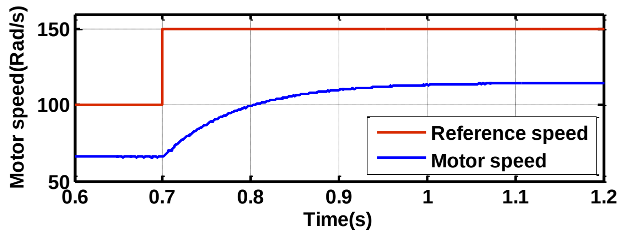


Fig. 8 - The dynamic response during the reference speed variation

RESULTS

To verify the proper operation of the proposed converter and its controllers for regulating the motor speed, a prototype system is simulated in MATLAB/Simulink environment. The system parameters and controller coefficients is the same explained in section III. The proposed power electronic system is connected in its AC side to a thee phase system with phase-null voltage of $120V_{(RMS)}$-60Hz. For proper operation of the PWM algorithm, this is required to the V_{C1} reference voltage at least be two time of the amplitude of the AC side phase-null voltage. Choosing the reference voltage of 400V for C_1, shoot through cycles in PWM algorithm is placed only in null vectors of (000) and (111) while the active vectors remain unchangeable. Moreover the rating voltage of the motor is considered to be 200V which must be regulated by the proposed converter system and its controllers. The rating speed and current of the motor are 1500RPM and 50A respectively. Operation of the proposed system for regulating motor speed is shown in Fig. 9. The motor speed is shown in Fig. 9 (a). As can be seen, the motor speed is equal to its reference of 100 (Rad/s). The motor's phase currents are shown in Fig. 9 (b). As it seen, the hysteresis current controller properly regulates the motor current to a certain value produced by sped controller. The motor voltage is shown in Fig. 9(c). As it clear, the motor voltage is regulated to its reference of 200V by motor voltage controller. In Fig. 9(c), addition to the high frequency ripples caused by switching, the voltage across the C_{DC} has somewhat low frequency ripples which are produced by commutation of the motor phases.

The controller performance for regulating the V_{C1} is shown in Fig. 10. The capacitor "1" voltage in steady state condition is shown in Fig. 10 (a). The capacitor voltage controller properly regulates its voltage to the reference voltage of the 360V. The inverter current in AC side is shown in Fig. 10 (b). As can be seen, the inverter current in AC side is completely balanced three phase voltage with sinusoidal wave forms which means the designed controllers for AC and DC side are functioning properly.

The operation of the system during dynamic transients is shown in Fig. 11. Here this is supposed to motor speed varied suddenly from 1000RPM to 1500RPM. The motor speed variation beside reference speed variation is illustrated in Fig. 11 (a). As it clear, the motor speed tracks its reference speed without any overshoot with zero steady state error. The necessary condition for proper operation of the motor speed controller and transferring power from converter to motor is to control the motor voltage to its reference. The voltage across the C_{DC} during variation in motor speed is shown in Fig. 11 (b). As it shown, despite increase in motor speed and load, the voltage across C_{DC} is set to its reference of 200V. The voltage across the C_1 is shown in Fig. 11 (c) which is regulated to its reference value. The proper regulation of the capacitor "1" voltage to its reference confirms the proper operation of the system in absorbing sinusoidal current from main grid which is shown in Fig. 11 (d).

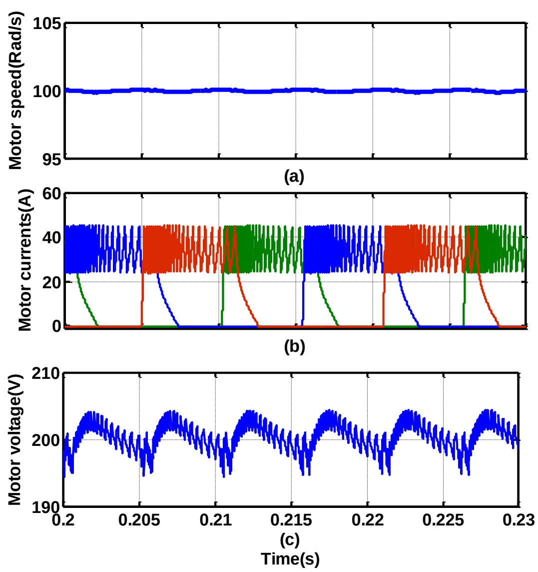


Fig. 9 - Motor variables during steady state condition, (a) motor speed, (b) motor phase currents, (c) motor voltage.

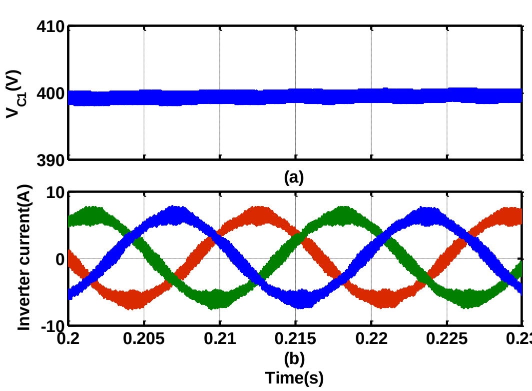


Fig. 10 - the converter variables in steady state, (a) Capacitor "1" voltage, (b) inverter current.

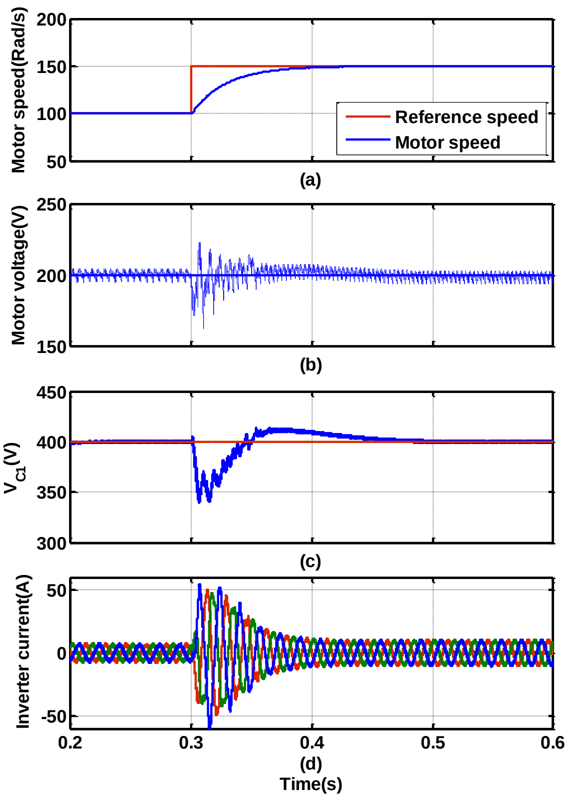


Fig. 11 - Dynamic response of the system during motor speed variation, (a) motor speed, (b) motor voltage, (c) capacitor "1" voltage, (d) inverter current.

CONCLUSION

In this paper a robust power electronic converter that controls the speed of motor has been introduced. To convert the AC voltage to the DC needed for SRM, asymmetrical Γ-Source inverter has been used. As it was shown, this type of inverter is able to convert AC voltage to the DC with lower amplitude of the source. Also the AC side current of this inverter is a three phase balanced, low harmonics current. To design suitable controller for mentioned converter the dynamic model of converter is used. Also to design suitable motor speed controller the dynamic model of motor around the operating point has been used. To this end time response of motor to the distortion has been used. The converter and designed control system performance has been investigated through relevant simulation in MATLAB/Simulink.

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