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Simulation and Comparative Assessment of Slip Power Recovery Scheme

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ABSTRACT: This research paper mainly focuses on the simulation of Static Scherbius Drive Scheme for efficient speed control using two methods viz. Inverter firing angle control and Chopper control. The main aim of this work is to find out the best and effective slip power recovery scheme. The methods which are taken into account are conventional slip power recovery scheme, slip power recovery scheme with variable transformer turns ration control and chopper control of slip power recovery scheme. Analyses of these schemes are done thoroughly with total harmonics distortion and speed control of rotor taken as parameters for study.

KEYWORDS*:* Doubly fed induction motor, Inverter firing angle, Slip Power Recovery Scheme and Static Scherbius Drive Scheme.

I. INTRODUCTION

IN1891, Nikola Tesla introduced a crude type of poly phase induction motor in Frankfurt exhibition. Since then induction motors are commonly used for control systems, in main home appliances and also in various industrial applications. Nearly 80% of the world's AC motors are poly phase induction motors. The main benefit of using induction motors is its simple and rugged construction, cost effectiveness, efficient working along with low maintenance, simplicity of control and direct connection to an ac mains.

Earlier, the nature of industrial applications of the induction motors were of constant speed mechanical drives (e.g. pumps, fans, blowers, conveyors, compressors etc.) due to difficult, costly and less efficient speed control; but, the recent advancement in power electronics components have provide the way for the development of power electronics based variable speed induction motor drives. Both types of induction motors i.e., i) Squirrel Cage & ii) Wound Rotor (or Slip Ring) have nearly replaced the conventional dc motor drives for variable speed applications [22]-[25].

The basic concept of slip power recovery (SPR) scheme was first presented, in 1966 [1]. The slip power recovery scheme analysis using thyristors was reported in [2]. The main lacing factors of this scheme has been inferred as the poor system power factor due to excess of reactive power drawn out of the source both by the motor as well as the line commutated inverter. For the purpose to overcome the drawbacks of poor power factor, several methods have been reported in literature. In [3] capacitive compensation approach was discussed. In [4] Static Scherbius Drive with chopper was presented. The required speed controlling in this method was obtained by time ratio control of the chopper unit for fixed value of inverter firing angle. However, it has been envisaged that in the absence of recovery transformer the current harmonic distortion in the supply system would increase. A new control technique for the minimization of losses of a doubly-fed induction motor by using optimal control techniques was introduced in [5]. The optimal control vector voltage leads to the improvement of overall drive performance and a method of energy saving for industrial processes operating with variable loads in the low speed range. Also a simple modeling approach that can predict the operation of a slip recovery drives in detail both in the steady state and in the transient state was presented in [6]. The hybrid model retained the actual rotor states and the algorithm used a 4th order Runga Kutta integration method.

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In [7] slip recovery drive performance, adaptive fuzzy techniques for improving the performance were given. Starting transients in slip energy recovery induction motor drives was given in [8]. In [9] the stability of slip power recovery system was shown. The detailed analysis of slip energy recovery induction motor along with a step-down chopper control technique was given in [10]. This approach comprised a hybrid model of the induction motor including a chopper controlled drive. In [11] a slip power recovery scheme arrangement using decoupled control of two different variables at the same time was presented. PWM voltage converter used on the line side is useful in controlling a wide range of reactive power and also lower down the current harmonic contents.

In this the performance of slip power recovery system by field and current space vectors was evaluated. The advantages of the circuit were low cost, the simplicity which allow the quasi optimum exploration of the induction motor, the method developed had the disadvantage of increasing the switching stresses of the switching devices, dissipative commutation and Complex control of the duty cycle [12]. Adaptive Fuzzy-neuro controller was used for speed control of wound rotor induction motor is utilized for slip power recovery and is evident in [13].

In [14], a controller with adaptive sliding-mode employed on induction machine drives for the sake of slip power recovery was developed using non-linear control approach. In this approach, the motor generated torque became linear with respect to system control states, the rotor flux could be easily regulated in order to increase the machine efficiency, and the system robustness could be achieved against the parameters uncertainty. In [15], a bi-converter arrangement through which supply is fed to doubly fed induction machine having two voltage source inverters (VSIs) supplying power to stator and rotor windings was developed.

An optimum circuitry and implementation of converter with high frequency performance along with induction motor was presented in [16]. High performance frequency converters enabled very effective motor control by providing the possibility of slip compensation as well as improvement of power factor of the system. In [17], the auto-disturbance-rejection-control is applied to the slip power recovery with chopper for induction motor drive. It is used as a speed regulator for dynamic performance improvement of conventional double-closed-loop PID control system. It was an effective method to improve the robustness and adaptability performance for induction motor. A method employing speed estimation for doubly-fed slip-ring induction motor drive connected to a grid was proposed in [18]. The method did not require any estimation of flux and also stator and rotor resistance variation were independent and less sensitive to noise. In [19] an adjustable speed drives to allow the DFIM operating in the full speed range. In grid synchronization method, the machine switched smoothly between different modes without inrush current. The principle and analysis of the variable power factor operation of a single fed induction machine with stator connected directly to the grid and power electronics in the rotor was given in [20]. It resulted in smaller size of the power electronic converter and the capacitors; the induction machine was operated at unity power factor at a particular torque and speed. In [21] a MIMO power control strategy based on Second Order Sliding Mode for a grid-connected variable-speed wind energy conversion system with slip power recovery was discussed.

Thus, it has been found that the slip power recovery scheme is a comprehensive case study. Thorough investigation of the prevailing slip power recovery scheme, its performance characteristics and control mechanism is required to be found using simulation for further improvements using different techniques.

II. BACKGROUND

A. Methods of Speed Control

The speed controlling methods of induction motor are distinguished as per the side of control i.e.

1. From the stator side
2. From the rotor side

From the stator side:

i. Applied voltage control: In this method, reduced voltage has been given to stator to get variable speed. For a constant load, reduced voltage reduces the torque produced resulting in reduced rotor speed.

ii. Pole changing control: In pole changing method, no. of stator poles has been changed electrically. As the speed of rotor is inversely proportional to number of poles, change in number of poles results in step change in rotor speed.

iii. Supply Frequency control: In this method, stator supply frequency has been changed. As the speed of rotor is directly proportional to supply frequency, change in supply frequency results in change in rotor speed.

The rotor side speed control method has been obtained by controlling the power dissipated in the rotor circuit, keeping the rotor input power (air gap power) as constant.

From the rotor side:

i. Rotor resistance control: The power dissipated by the rotor is controlled by connecting external resistance to the rotor. By changing the external resistance, variation in speed has been achieved. The disadvantage of this method is additional heat loss in external resistance resulting in reduced efficiency of the system.

ii. Slip power recovery control: In this method, some of the rotor power has been recovered from the slip rings and feedback to the power supply through converter and inverter circuit. The amount of feedback power (and hence the speed of the rotor) is controllable thus providing increased efficiency of the system.

The above listed stator side control methods have been applicable for squirrel cage and rotor side control methods have been applicable to wound rotor (slip ring) induction motors [23]-[25].

B. Speed Control Using Slip Power Recovery Scheme

The basic slip power recovery scheme comprising Static Scherbius Drive is shown in Figure 1. This scheme provides speed control of a slip ring induction motor below synchronous speed N_s.

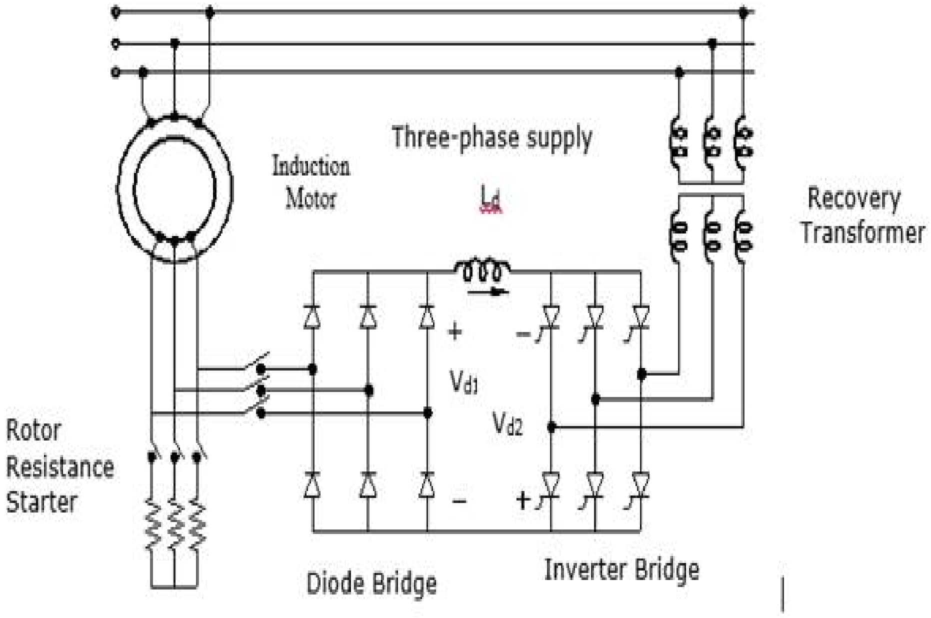

Figure 1 Circuit Diagram of Slip Power Recovery Scheme

A portion of rotor power is converted by a three-phase full-wave diode bridge rectifier. The three-phase full-wave fully controlled thyristor bridge working as line commutated inverter, inverts this power and fed back the same to the three-phase ac source. This feed-back power can be controlled by varying the inverter emf V_{d2}, which can be varied by changing the firing angle of the three-phase inverter bridge.

The dc line inductor L_d is provided to reduce ripples in dc link current I_d. Since, slip power is fed back to the source; the scheme eliminates wastage of energy and therefore has higher efficiency [24], [25].

Neglecting stator and rotor drops,

$$V_{d1} = \frac{3\sqrt{6}}{p} \cdot \frac{sV}{n} \qquad (1)$$

$$V_{d2} = \frac{3\sqrt{6}}{\pi} \cdot \frac{V}{m} \cdot cos\alpha \qquad (2)$$

here,

V_{d1} is the output voltage of diode bridge rectifier
V_{d2} is the output voltage of Inverter Bridge
α is the inverter firing angle
n is the stator to rotor turns ratio
p is the no. of phases
m is source to converter side turns ratio of the transformer
s is the slip

V is the supply voltage
Neglecting drop across the inductor,

$$V_{d1} + V_{d2} = 0 \qquad (3)$$

From equations 1 to 3, the value of slip‘s’ will be given by:

$$s = -\frac{n}{m} cos\alpha \qquad (4)$$

From the above equations, it can be seen that:
i. Maximum value of α has been restricted to 165^{o} for safe commutation of thyristors [25]. Slip can be controlled from *0* to $0.996\frac{n}{m}cos\alpha$, when α is varied from 90^{o} to 165^{o}. By appropriate choice of α, required speed can be obtained. A transformer has been used to match the voltages V_{d1} and $V_{d2}$by taking a suitable turns ratio [25]. By varying firing angle ‘α’ the speed of the scheme will be varied.
ii. Similarly, by placing a step-down chopper between the dc link voltages V_{d1} & V_{d2} the speed control of the scheme will be obtained.
Equation 4 reveals that the slip (and hence speed) of the scheme depends upon the turns ratio ‘*m*’ of the transformer. Hence by varying this turns ratio, the speed of the scheme will be varied.

C. Chopper Controlled Slip Power Recovery Scheme

A chopper is a static device that converts fixed dc input voltage to a variable output voltage directly. A chopper is a high speed semiconductor switch, which connect s source to load at fast speed and vice-versa. For the chopper configuration, when average output voltage $V_0<V_s$ (input voltage), it is called step-down chopper and if $V_0> V_s$ it is called step-up chopper.
For step-down chopper

$$V_o = \frac{T_{on}}{T_{on}+T_{off}} = \frac{T_{on}}{T} = \delta V_s \qquad (5)$$

Where, $\delta = \frac{T_{on}}{T}$=duty ratio, V_s=Source voltage and V_o=Load voltage.

For step-up chopper,

$$V_o = V_s\frac{1}{1-\delta} \qquad (6)$$

From equation (5) and (6), it is clear that output voltage can be control by controlling duty ratio δ.
The various strategies for controlling the duty ratio δ are:
a) Time Ratio Control or Pulse-width-modulation scheme, in which T_{on} is varied and chopping period is kept constant means adjustment of pulse width.
b) Frequency-modulation scheme, in which chopping frequency f is varied and either T_{on} or T_{off} is kept constant.

III. METHODOLOGY

A. Modeling and Simulation Process for line commutated inverter controlled SPR Scheme

a) The simulation is carried out for the selected motor.
b) Initially, the firing angle of the synchronized 6-pulse generator has been selected as 91°.
c) T-ratio is kept as 100/400 and no chopper is placed within the dc link voltage circuit.
d) By increasing the firing angle from 91° (at constant load), change in speed and other parameters has been observed.

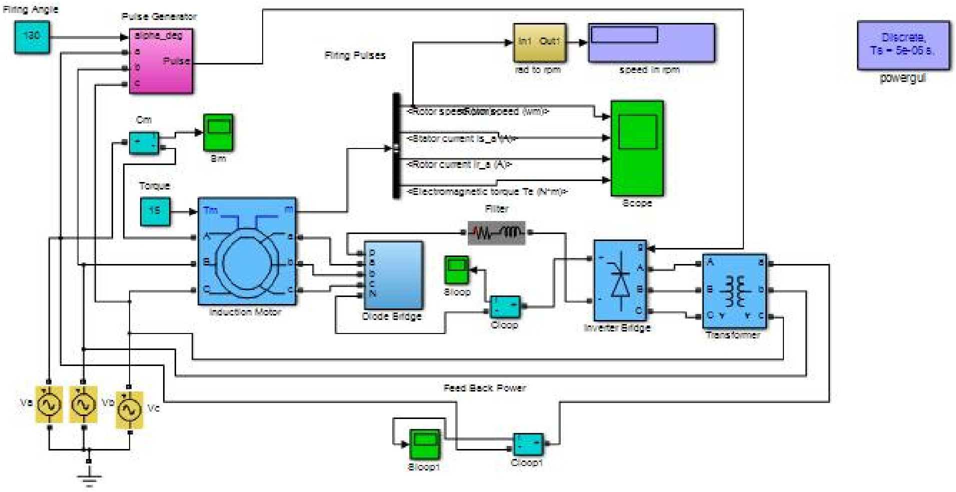

Figure 2 Simulation Model of Slip Power Recovery Scheme with Inverter Control

B. *Modeling and Simulation Process for Chopper controlled SPR Scheme*

a) Initially, the firing angle of the synchronized 6-pulse generator has been selected as 90°.
b) T-ratio is kept as 100/400 and Mosfet based chopper is placed within the dc link voltage circuit.
c) By decreasing the duty ratio of the chopper (from 100 to say 5%), change in speed and other parameters have been observed.

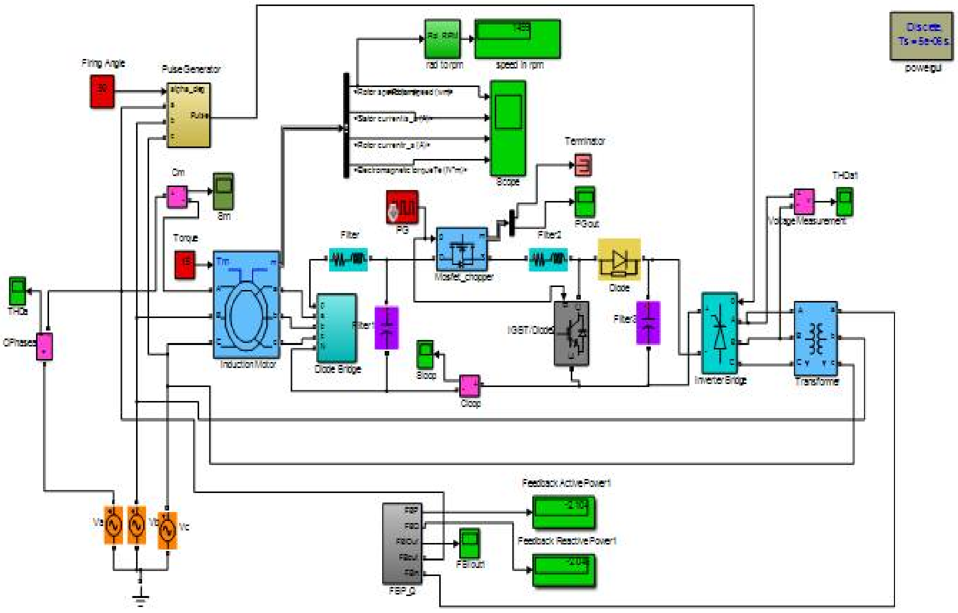

Figure 3 Simulation Model of SPR Scheme with Chopper Control

IV. RESULTS AND DISCUSSIONS

A. *Results of Line Commutated Inverter Controlled SPR Scheme*

Table I. Results of line commutated inverter controlled SPR Scheme

SN	Fang (Degree)	Speed (RPM)	THDa (%age)	THDfb (%age)	FBP (W)	FBQ (VAR)
1	90	1450	5.14	29	1	-227
2	95	1421	7.68	29.71	22	-217
3	100	1383	6.12	29.75	41	-220
4	105	1348	7.25	29.86	58	-210
5	110	1313	8.61	29.94	77	-206
6	115	1278	10.09	29.67	98	-205
7	120	1243	5.29	29.73	114	-192
8	125	1216	6.6	29.8	127	-177
9	130	1189	8.69	29.65	142	-165
10	135	1163	9.04	29.65	155	-151

The above table I gives the results obtained for SPR Scheme with inverter control. It is to be remembered that during this simulation, the firing angle of the line commutated inverter is varied whereas transformer ratio is kept constant (100/400, inverter to line side). Also, the chopper is not introduced at this stage.

Here,
Fang =Firing angle of the inverter
THDa = THD of the source current
THDfb = THD of the feedback current
FBP = Feedback Active power
FBQ = Feedback reactive power

The results are plotted for better understanding of the working of the scheme. Figure 4(a) shows the effect of change in firing angle over the speed of the drive. It is clearly seen that increase in inverter firing angle over 90˚ the speed of the drive reduces linearly. This type of characteristic is analogues to armature current-speed characteristics of a dc shunt motor where armature (here rotor) current is independent of field (here stator) current.

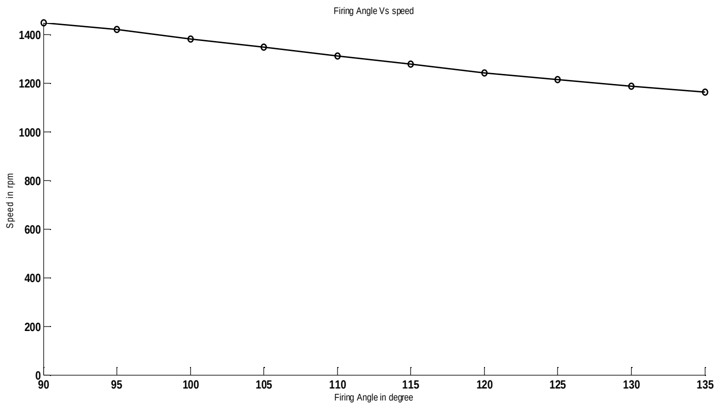

Figure 4(a) Graph between Fringing Angle and Speed

Figure 4(b) shown below is the graph between firing angle and feedback active power which is again a linear relation i.e. increase in firing angle results in increase in feedback power and decrease in rotor speed.

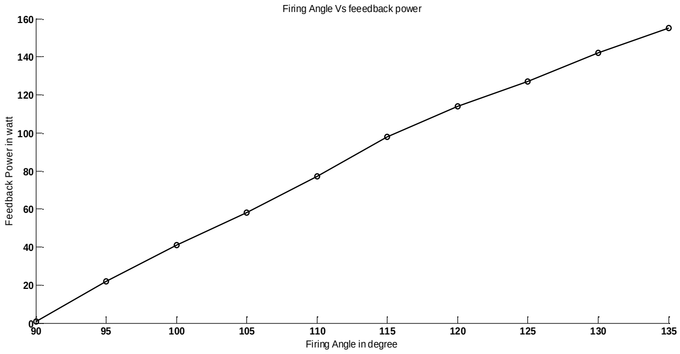

Figure 4(b) Graph between Fringing Angle and Feedback Active Power

Figure 4(c) below shows the reactive power requirement of the scheme at various firing angles. It is seen that the reactive power required for the inverter reduces as the firing angle increases (or as the speed decreases. Hence overall power factor of the scheme increases with decrease in speed.

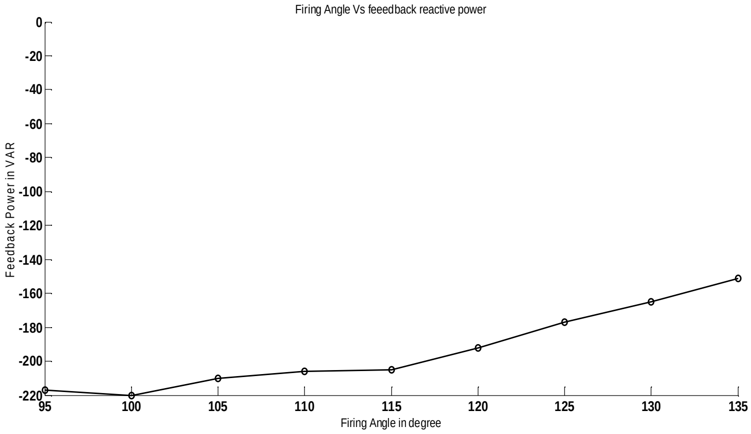

Figure 4(c) Graph between Fringing Angle and Feedback Reactive Power

B. Results of Chopper controlled SPR Scheme

Table II. Results of Chopper Controlled SPR scheme

SN	Duty Cycle	Speed (RPM)	THDa (%age)	FBP (W)	FBQ (VAR)
1	60%	1431	3	90	-150
2	50%	1417	4.07	193	-326
3	40%	1387	7.35	287	-426
4	30%	1337	7.45	317	-490
5	20%	1240	3.61	194	-446
6	10%	1130	6.29	37	-176
7	5%	1034	7.25	4	-53

It should be noted that during this simulation, the firing angle of the line commutated inverter is fixed at 90 degrees, transformer ratio is kept constant (100/400, inverter to line side).

The Table II gives the tabular analysis of Chopper controlled SPR Scheme. Chopper is introduced at this stage with variable duty-ratio.

Figure 5(a) shows the effect of change in duty ratio over the speed of the drive. It is clearly seen that increase in duty-ratio below 100, the speed of the drive reduces almost linearly. Also, the change in speed is large as compared to t-ratio control.

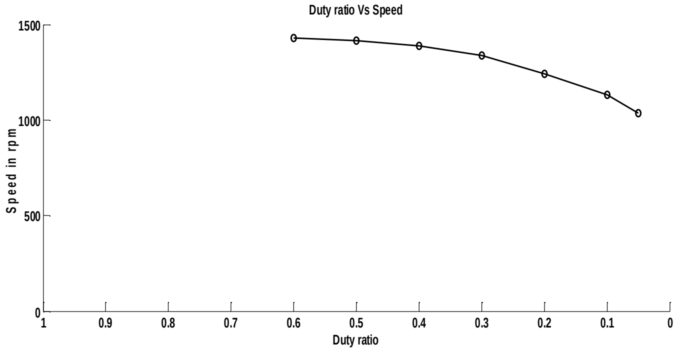

Figure 5(a) Graph between Duty Cycle and Speed

Figure 5(b) below shows the active feedback power for various duty-ratios. It is seen that the active feedback power increases as the duty-ratio increases for moderate change in speed, whereas, feedback power reduces drastically at reduced speeds.

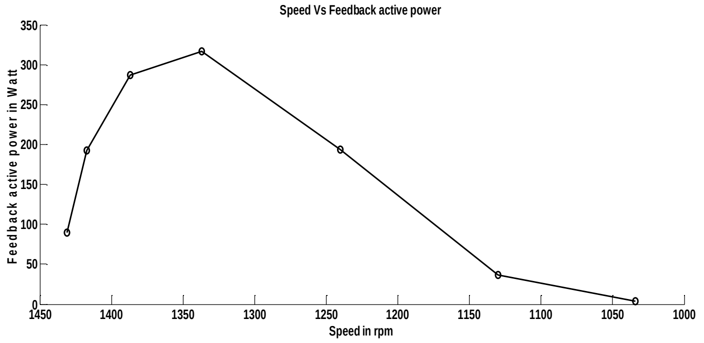

Figure 5(b) Graph between Speed and Feedback Active Power

Figure 5(c) below shows the reactive power fed to the scheme for various duty-ratios. It is seen that the reactive power increases as the duty-ratio increases for moderate change in speed and the reactive power reduces drastically at reduced speeds.

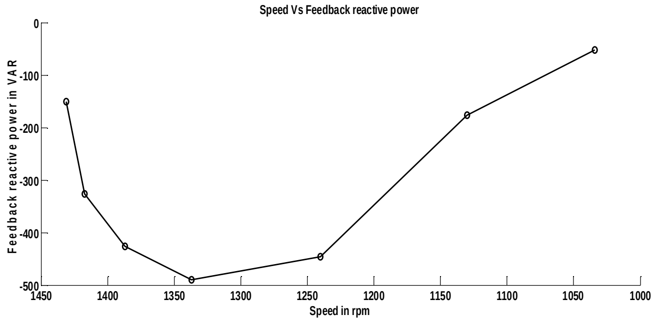

Figure 5(c) Graph between Speed and Feedback Reactive Power

V. CONCLUSION

The simulation of the Static Scherbius Drive is able to achieve the speed control for the two methods viz. i) Inverter firing angle control and ii) Chopper control. Reactive power required for the inverter circuit is high, especially at low inverter firing angle. Inverter firing angle control & chopper control offers vide range speed control. Hence, chopper based scheme is found to be best among both schemes. The requirement of operation of motor at variable speed with reduced reactive power and lower value of THD can be met with by using a latest technology of multi-level inverter. This can help to get a variable speed at maximum power factor& lower THD levels. At the same time, size and cost of the converter and inverter circuit can be kept low for a definite speed range. Further research and investigation towards this aspect is solicited.

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