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NOVEL IsinΦ CONTROLLER BASED THREE PHASE REACTIVE POWER COMPENSATOR FOR WIND ELECTRIC GENERATOR

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Abstract- ***The conventional energy sources for electrical power generation are water, fossil fuels, and nuclear energy. However, the earth's environment has been seriously damaged due to the excessive usage of these energy sources; and since the supply of fossil fuels will be exhausted in the future, their costs will increase evidently. Hence, renewable energy sources, such as wind and solar are becoming increasingly important. Because the cost of wind power is dropping very fast to the point where it is very close in cost to conventional electric power generation, wind power use has recently rapidly increased worldwide. The induction generator is generally applied in the wind turbine industry. But induction generator suffers from a disadvantage of having low power factor. In this paper a three phase reactive power compensator based on proposed IsinΦ algorithm for wind electric generator is introduced. It provides reliable and effective reactive power compensator for low rating VSI. The design, selection of elements, fabrication and testing of three phase two leg reactive power compensator are explained in this paper. The performance and effectiveness of IsinΦ algorithm is verified by simulation and experimental results. The controller designed, ensures that balanced sinusoidal and in phase currents are drawn from the three phase supply.***

Keywords: Reactive power compensator, Wind Electric Generator, Voltage Source Inverter

INTRODUCTION

Wind power is now increasingly accepted as a major complementary energy source for securing a sustainable and clean energy future for India. India is the 3rd largest annual wind power market in the world. India had another record year of new wind energy installations between January and December 2011, installing more than 3 GW of new capacity for the first time to reach a total of 16,084 MW. As of March 2012, renewable energy accounted for 12.2 percent of total installed capacity, up from 2 percent in 1995. Wind power accounts for about 70 percent of this installed capacity. By the end of August 2012, wind power installations in India had reached 17.9 GW. Presently, India has an installed power generation capacity of a little over 207.8 GW, of which renewable account for about 25 GW, and wind makes up a majority of this installed capacity. In 2011 the state-run Centre for Wind Energy Technology reassessed India's wind power potential as 102,778 MW at 80 metres height at 2% land availability, up from the earlier estimate of approximate 49,130 MW at 50 meters, also at 2% land availability. If the estimated potential of 102 GW were fully developed, wind would provide only about 8 percent of the projected electricity demand in 2022 and 5 percent in 2032 [1].

The variability of wind power can create problems for the traditional grids in maintaining a supply and demand balance. Most of the wind farms in India are located in remote areas that are quite far away from load centers. Due to a weak transmission and distribution network, it is difficult to transmit the power from wind farms to the load dispatch centers. This is one of the key constraints for the future of wind power development in the country.

There are a range of advantages and disadvantages of wind energy to look at, including the many problems associated with wind turbines. Newer technologies are making the extraction of wind energy much more efficient. The wind is free, and we are able to cash in on this free source of energy. Wind turbines are a great resource to generate energy in remote locations, such as mountain communities and remote countryside. Wind turbines can be a range of different sizes in order to support varying population levels. The main disadvantage regarding wind power is down to the winds unreliability factor. If the wind farms would be installed solely to maximize energy output they would have major limitations in terms of voltage and reactive power control, frequency control and fault ride-through capabilities. These are the three main points that new grid codes must adapt for wind farm connection. The most worrying problem that wind farms must face is a voltage dip in the grid. The effects of transient faults may propagate over very large geographical areas and the disconnection of wind farms under fault conditions could pose a serious threat to network security and security of supply because a great amount of wind power could be disconnected simultaneously. A mismatch between the supply and demand of reactive power results in a change in the system voltage: if the supply of lagging reactive power is less than the demand, a decrease in the system voltage results; conversely, if the supply of lagging reactive power exceeds the demand, an increase in system voltage results [2]. The wind farm should have the capability to control the voltage and/or the reactive power at the connection point.

There are several reactive power compensation techniques. Capacitor bank is the simplest reactive power compensator. But it cannot compensate reactive power under dynamic load conditions. For some load conditions it may lead to over compensation and sometimes it may lead to under compensation. The reactive power compensation can be adjusted linearly by controlling the firing angle of the thyristor switch in other technology, such as fixed-capacitor thyristor-controlled-reactor (FC-TCR). However, this method will generate a harmonic problem, because the thyristor switch cannot conduct a full cycle. In order to solve the application problems of the ac power capacitors used for reactive power compensation, the power converter- based reactive power compensator was developed [3]–[5]. Later three phase voltage source inverter based reactive power compensator was developed [6]. To reduce the rating of the compensator a two leg inverter topology to compensate three phase reactive power was previously developed [7]. The proposed reactor employs an ac power capacitor set serially connected to a power converter and has the following advantages:

1) No power resonance problems;
2) Small capacity of power converter;
3) Less power electronic switches in the power converter.

In this paper a novel control strategy of IsinΦ algorithm is incorporated to the two leg inverter topology to compensate three phase reactive power. The proposed control algorithm is more effective and simple logic to compensate three phase reactive power.

VARIATION OF REACTIVE POWER WITH THE SPEED OF WIND

During the normal operation, wind turbine produces a continuous variable output power. These power variations are mainly caused by the effect of turbulence, wind shear, and tower-shadow and of control system in the power system. Thus, the network needs to manage for such fluctuations. The power quality issues can be viewed with respect to the wind generation, transmission and distribution network, such as voltage sag, swells, flickers, harmonics etc. However the wind generator introduces disturbances into the distribution network. One of the simple methods of running a wind generating system is to use the induction generator connected directly to the grid system. The induction generator has inherent advantages of cost effectiveness and robustness. However, induction generators require reactive power for magnetization. When the generated active power of an induction generator is varied due to wind, absorbed reactive power and terminal voltage of an induction generator varies. A proper control scheme in wind energy generation system is required under normal operating condition to allow the proper control over the active power production. A simulation in MATLAB/SIMULINK was carried out to determine the variation of reactive power drawn from the supply with variation in wind speed. The test system is as shown in fig.1 and the results obtained are tabulated in table 1.

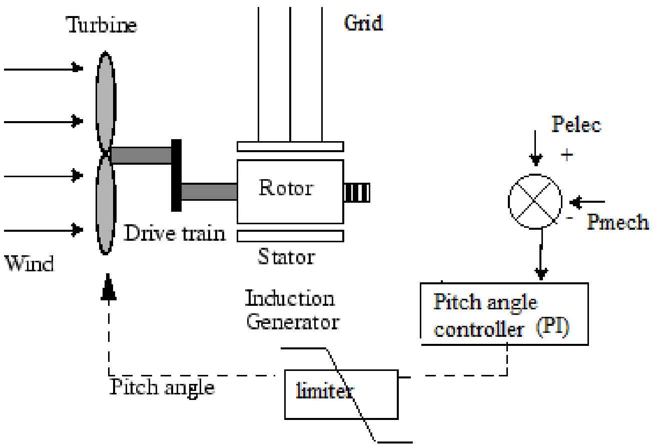


Fig.1: Test system selected for the study of variation of reactive power with triggering angle.

Table 1 Test system specifications

Power rating	3HP
Switching frequency	10kHz
Rotor resistance	1.24Ω
Stator resistance	1.517Ω
V_{dc}	1300V
Base frequency	100Hz
Stator Leakage Reactance	5.12Ω
Rotor Leakage Reactance	120Ω
No. of poles	4
Moment of Inertia	0.2kgm^2

Table 2 Variation of reactive power demand of induction generator with wind speed

Wind speed (m/s)	Generated Power (p.u.)
5	0.125
10	0.75
15	1
20	1
25	1

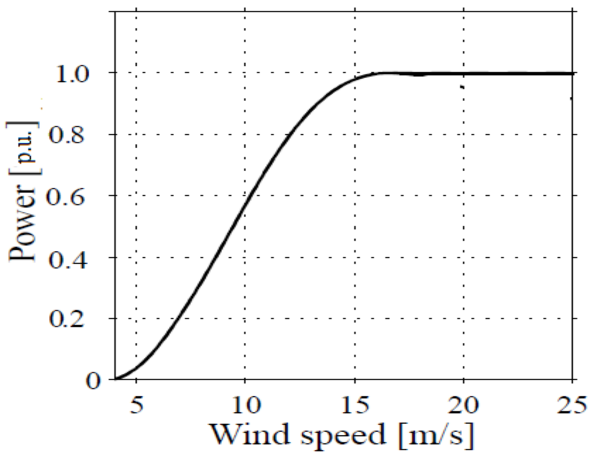


Fig.2. Variation of reactive power with wind speed

The stator winding of three phase induction generator is connected to three phase 50Hz grid and rotor is driven by a pitch controller based wind turbine. The wind power is converted to electrical power by the induction generator and transmitted to the three phase grid through the three phase stator windings. The pitch angle is controlled in order to limit the generated output power to its normal value for high wind speeds. The test system specifications are shown in Table 1.Fig. 3 and Fig.4. shows source current and voltage waveform under two different system conditions- slip=-3% (case I) and slip = -2%(Case II).The results show that significant reduction in power factor under both the conditions. Hence, this paper presents Novel Isinϕ controller based three phase reactive compensator, which are described in detail in coming sections.

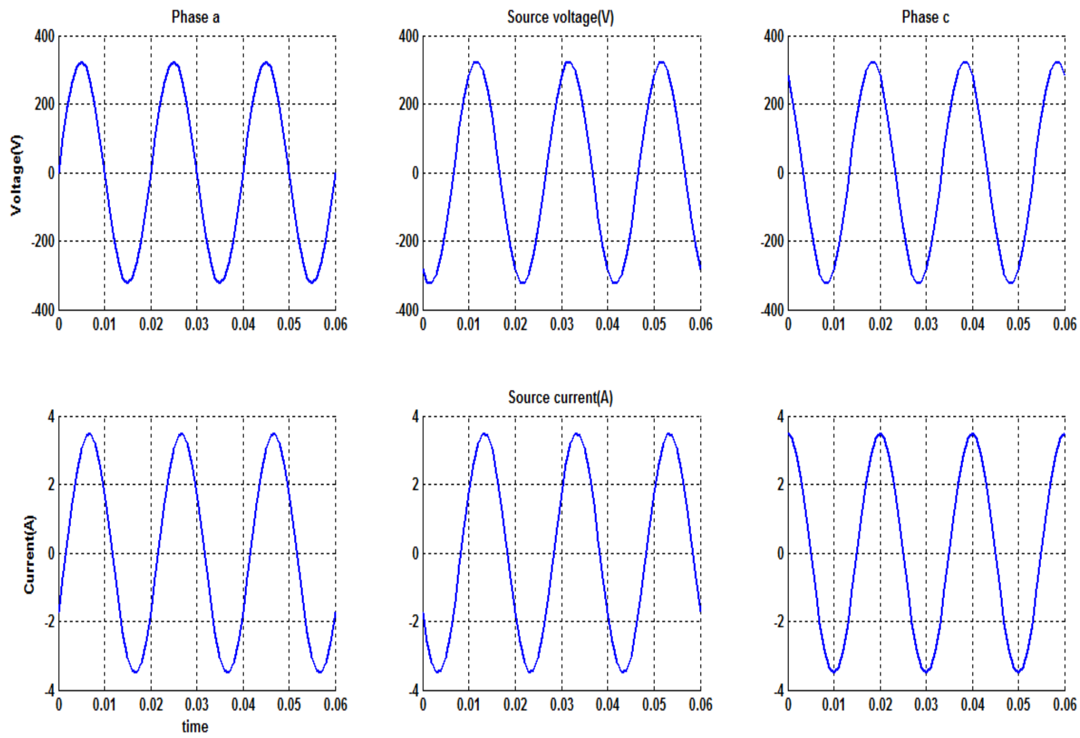


Fig. 3. Phase source voltages and source currents without any compensation –Case I

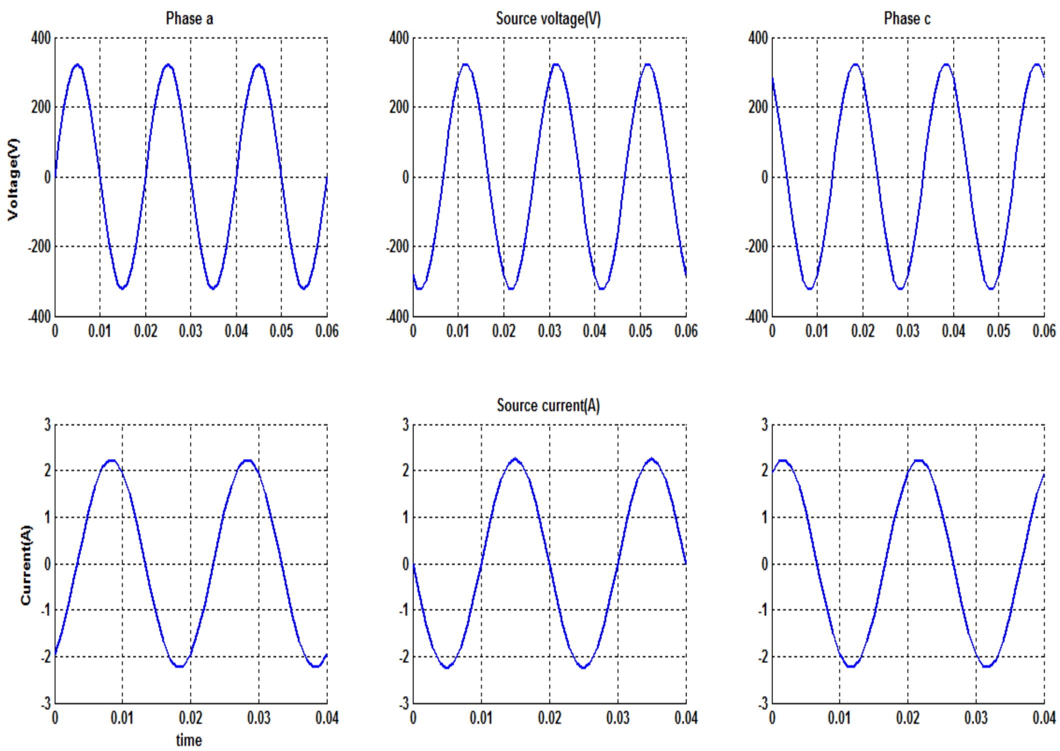


Fig. 4. Three phase source voltages and source currents without any compensation –Case II

ISINΦ CONTROLLER BASED REACTIVE POWER COMPENSATOR

According to the proposed IsinΦ control algorithm, the mains is required to supply only the active component of load current and the reactive power of the load is met by IsinΦ controller based three phase two leg inverter.

Assuming a balanced source, the three phase instantaneous fundamental component of voltages can be represented by

$$v_a = V_m \sin \omega t \; ; v_b = V_m \sin(\omega t - 120°) \; ; v_c = V_m \sin(\omega t + 120°) \quad (1)$$

a, b, c = phases a, b, c, respectively
V_m = peak value of the instantaneous voltage
When balanced three phase supply feeds a non-linear reactive load, the load current contains fundamental and harmonic components.

$$i_{La} = I_{La} \sin(\omega t - \phi_a) \quad (2)$$

$$i_{Lb} = I_{Lb} \sin(\omega t - \phi_a) \quad (3)$$

$$i_{Lc} = I_{Lc} \sin(\omega t - \phi_a) \quad (4)$$

where,
a, b, c = phases a, b, c, respectively
i_L = instantaneous load current in phases a, b,c
I_L = peak value of h^{th} harmonic component of load current
ϕ = Phase angle of the h^{th} harmonic component with respect to voltage

The fundamental component of the load current is separated with the help of biquad low pass filter. Its output is fundamental component is delayed by 90° during the filtering operation.

$$i_{La} = I_{La,1} \sin(\omega t - \phi_{1a} - 90^0) \quad (5)$$

$$i_{Lfb} = I_{Lb,1} \sin(\omega t - \phi_{1b} - 120° - 90^0) \quad (6)$$

$$i_{Lfc} = I_{Lc,1} \sin(\omega t - \phi_{1c} + 120° - 90^0) \quad (7)$$

The real part of the fundamental component of load current is estimated as follows:

At the time of negative peak of the input voltage of any one phase, say a phase, i.e., at ωt = 270°, instantaneous value of fundamental component of load current is the peak value of reactive component of the fundamental load current. Similarly, instantaneous values of fundamental components of phase b load current at ωt = 30° and phase c load current at ωt = 150° are the respective real components. The reactive part of fundamental component of load current is updated in every cycle.

The magnitude of the desired reactive compensation current $|I_{s(ref)}|$ is the magnitude of reactive part of the fundamental component of load current in the respective phases.

The voltage fluctuations in DC bus voltage of active filter are also sensed and given to PI controller, which calculates the current to be taken from the source to meet power loss in the inverter and coupling inductor. This current is added to the average value of reference compensation current $|I_{comp(ref)}|$. The three phase source voltages are used as templates to generate unit amplitude sine waves in phase with source voltages and they are expressed as,

i.e. $$U_a = 1 \sin \omega t \quad (8)$$

$$U_b = 1 \sin(\omega t - 120°) \quad (9)$$

$$U_c = 1 \sin(\omega t + 120°) \quad (10)$$

The desired (reference) source currents in the three phases are obtained by multiplying reference source currents with unit amplitude templates of the phase to ground source voltages in the three phases respectively.

$$i_{compa(ref)} = \left|I_{com(ref)}\right| \times U_a = \left|I_{comp(ref)}\right| \sin \omega t \quad (11)$$

$$i_{compb(ref)} = \left|I_{comp(ref)}\right| \times U_b = \left|I_{comp(ref)}\right| \sin(\omega t - 120^o) \quad (12)$$

$$i_{compc(ref)} = \left|I_{comp(ref)}\right| \times U_c = \left|I_{comp(ref)}\right| \sin(\omega t + 120^o) \quad (13)$$

The block diagram representation of control logic is shown in fig.5.

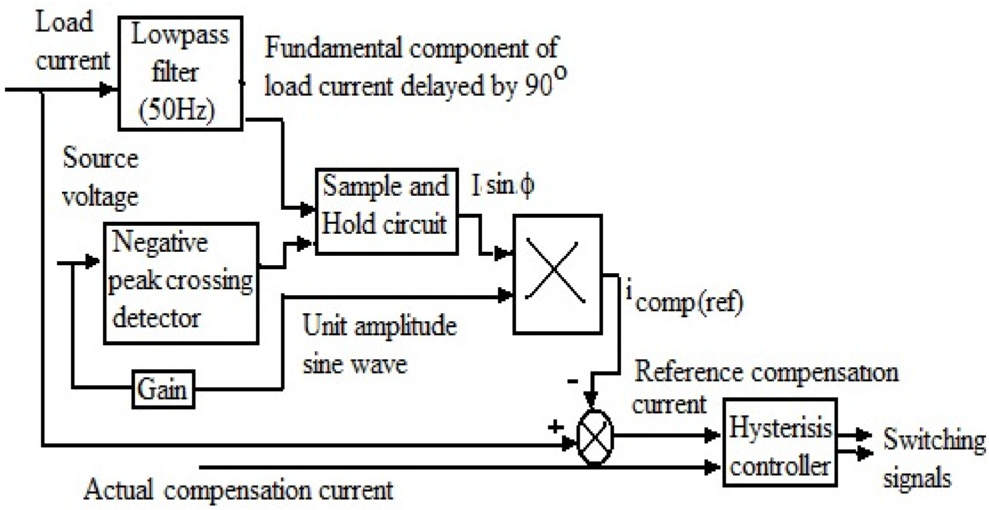


Fig. 5. Basic block diagram to capture IsinΦ component of load current

MODELING OF THE TEST SYSTEM

a. Wind Turbine:

Wind turbine converts available wind energy to mechanical energy. It consists of gearbox and pitch controller circuit. Gear box helps to match the turbine speed with the generator speed. Pitch angle controller controls the amount of power to be converted. The wind turbine mechanical power output is a function of rotor speed and wind speed and is expressed as

$$P_m = C_p(\lambda, \beta)\rho \frac{A}{2} v^3 \quad (14)$$

C_p = power coefficient of performance

ρ = density kg/m^2

v = wind speed m/s

A = swept area m^2

P = pitch angle

λ = tip speed ratio

b. Induction generator:

Induction generator is mostly used as wind electric generator. It converts the mechanical energy to electrical energy and supplies to the grid. The equivalent circuit if induction motor is shown in Fig.6.

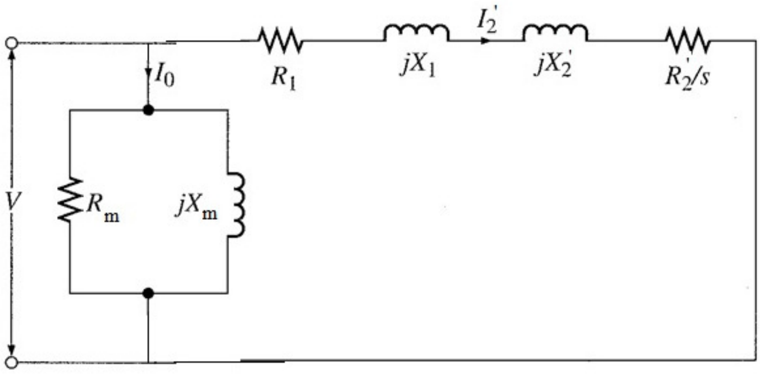


Fig. 6. Equivalent circuit of induction motor

From the equivalent circuit, electrical power is converted into mechanical power. As the power generation varies, reactive power demand from the supply varies. Hence variable reactive compensator with variation in generated power is necessary. It is provided by single phase inverter with suitable control algorithm.

c. Three phase two leg phase inverter:

Three phase balanced supply voltages are assumed. Let the three phase supply voltages be

$$v_a = V_m \sin \omega t \;; \quad v_b = V_m \sin(\omega t - 120°) \;; \quad v_c = V_m \sin(\omega t + 120°) \tag{15}$$

The three phase reference

$$i_a = I_m \sin \omega t \;; \quad i_b = I_m \sin(\omega t - 120°) \;; \quad i_c = I_m \sin(\omega t + 120°) \tag{16}$$

The following equations represent loop equations of three phase reactive compensator.

$$\begin{cases} L\dfrac{di_a}{dt} = V_a - ri_a - V_{aN} \\ L\dfrac{di_b}{dt} = V_b - ri_b - V_{bN} \\ L\dfrac{di_c}{dt} = V_c - ri_c - V_{cN} \end{cases} \tag{17}$$

The IsinΦcontroller based three phase reactive compensator provides effective compensation such that three phase source voltages and source currents are in phase.

d. Selection of coupling inductor:

A full bridge voltage source PWM inverter requires a dc bus capacitor and an inductor L_F, which is required to limit the rippleon the compensator current i_F.

$$L_F \frac{di_F}{dt} = V_F - V_S \tag{18}$$

where V_S and V_F are the supply and input filter voltages.

$$v_s = V_S \sqrt{2} \sin \omega t$$

$$v_F = \sigma V_c \text{ with } \sigma = 1, 0 \text{ or } -1.$$

To control the current i_F at each moment, it is necessary that the dc bus voltage V_c is kept higher than the maximum voltage imposed by the supply network, therefore

$$V_c \geq K\,(1+\varepsilon)\; V_S \tag{19}$$

where V_s = nominal peak voltage of the network

ε = voltage variation (10%)

K= over voltage factor (1.5<K<2)

The current imposed by the compensator i_F must contain two components:

- The fundamental active current, which is necessary to compensate the losses in the inverter and maintain constant terminal voltage across the capacitor
- All reactive and harmonic current to compensate the non- linear load.

The expression for current gradient i_F generated by the compensator shows that it depends on two parameters V_c and V_S that must be fixed. The value of V_C is constrained by the voltage rating of the switching devices. Therefore K is fixed at 2 taking into account the voltage variation and system dynamics [13].

$$V_C = 2V_S$$

$$L_F \frac{di_F}{dt} = (2\mathrm{d}-1)V_c - V_s$$

where d is the duty cycle

e. Selection of dc link capacitor:

It is considered that all the energy variation occurs in the capacitor C_F

$$\mathrm{dw} = \mathrm{d}\left(\frac{1}{2} C_F V_C^2\right) \tag{20}$$

$$\text{let} \frac{\Delta V_C}{V_c} < \varepsilon_{dc}$$

then $C_F > \frac{\Delta W_{\max}}{\varepsilon_{dc} V_c^2}$ where ε_{dc} is the maximum value of the V_C voltage ripple

SIMULATION RESULTS

From table 1, it is evident that as triggering angle increases or when speed of wind increases the reactive power drawn by the induction generator varies. As triggering angle (α) increases current drawn per phase (I_{ph}) varies. Reactive power Q= $3V_{ph}I_{ph}\sin\Phi$ also varies. Therefore the control logic should be able to trace the variation in reactive power and should compensate effectively. The value of capacitor to be connected in each phase is determined from the reactive power drawn. Taking all readings into consideration the value of capacitor to be connected in each phase is selected as 150μF.

The controller requires the following steps to be accomplished for the generation of the reference compensation signals.

1. Sensing the load current and phase voltages in the three phases.
2. Computation of amplitude of reactive component of load current.
3. Generation of unit amplitude sine waves in phase with phase voltages.
4. Computation of reference compensation current
5. Generation of firing pulses for the power converter.

The fig.7 shows the basic set up to be implemented in simulation as well as in hardware circuit.

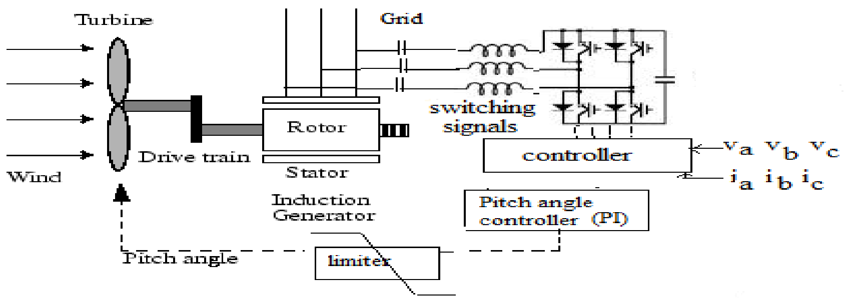


Fig. 7. Experimental setup for Isinϕ controller based three phase reactive compensator

Simulation results with compensation are shown in Fig. 8 and Fig.9. The source current in this case is exactly 180º phase shifted thereby making the reactive component equal to zero. Method to capture IsinΦ component of load current is simple and efficient. It can be implemented easily using analog as well as digital circuits. This method is applicable in all the operating conditions of the three phase system such as balanced, unbalanced and distorted source voltage and non-reactive as well as reactive, balanced as well as unbalanced non-linear loads

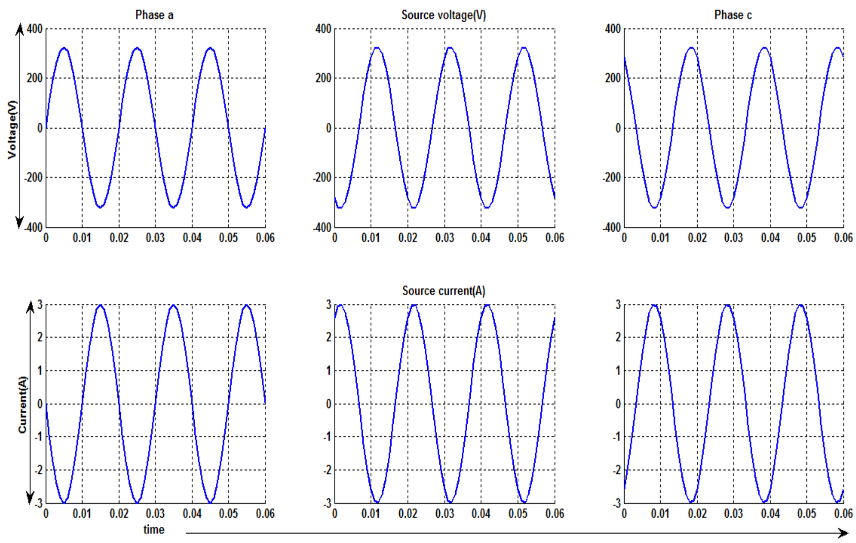


Fig. 8. Three phase source voltages and source currents with reactive compensation –Case I

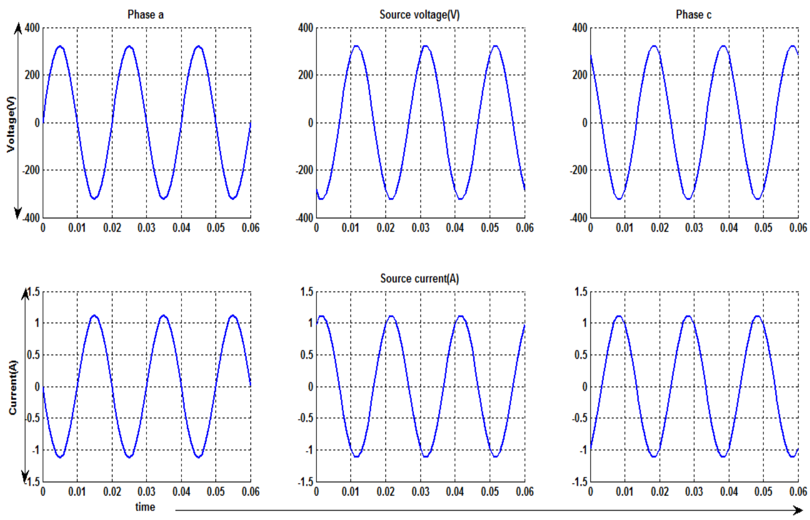


Fig. 9. Three phase source voltages and source currents with reactive compensation –Case II

From the simulation results it is evident that without compensator, at a slip of -3%, supply current lags the supply voltage by a significant angle. With compensator, the phase difference between voltage and current is zero. This highlights the effectiveness of compensator. The current supplied by the mains is purely the active component and the reactive component of the load is supplied by the compensator.

EXPERIMENTAL SET UP

Analog circuits are well known for their accurate and instantaneous response without any propagation delay. However, in the long run, analog circuits are susceptible to malfunctioning due to offset in the electronic circuits, tolerances of the components caused by heating. The offset can be nullified by using suitable biasing circuits and high precision operational amplifiers. The main advantages of using analog circuits are easy availability, cost effectiveness of analog circuits for implementing any mathematical function and very quick response with simple implementation aspects.
The squirrel-cage induction generator has the advantages of low cost and high durability; it is still a possible choice for wind power generation. However, its power factor is very poor. In order to verify the performance of the proposed reactive power compensator for a squirrel-cage induction generator, a three-phase prototype with a utility line voltage of 220 V and a utility frequency of 50 Hz is developed. The power rating of the squirrel-cage induction generator is 3 HP, 4.5A, 1440rpm. 230V, 19A, 5HP, 1500 rpm DC motor is used to drive this squirrel-cage induction generator. Name plate details are as given.
To establish a magnetic field in the rotor of a squirrel-cage induction generator, it requires an external reactive power supply to sustain self-excitation. This reactive power can be supplied from the utility in a grid-connected squirrel-cage induction generator.
The control circuit comprises of the following:

1. Biquad filter for extracting the fundamental component from load current.
2. Negative peak detector circuit to generate trigger at wt=180º
3. Sample and hold circuit
4. Multiplication circuit
5. Comparator circuit to generate PWM pulses for inverter

a. Biquad Filter:

Low pass filtering for extracting fundamental component of load current is the main operation to be done by the controller. Low pass filtering is done by the biquad filter. The advantages of using biquad filter, rather than other low pass filters, are it is easy to design, it gives unity gain and it also gives exact 90° phase shift. Following session gives the design of biquad filter.

b. Design Of The Biquad Filter:

The biquad filter is a family of op-amp RC circuit that realizes second order filter function. The circuits are based on the use of two integrators connected in cascaded in an overall feedback loop and are thus known as two integrator loop biquadratic circuit or biquad [8]. To derive the biquad consider second order high pass transfer function

$$\frac{V_{hp}}{V_i} = \frac{Ks^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2} \tag{21}$$

where K is the high frequency gain. Rearranging, equation (21) become

$$\frac{V_{hp}}{V_i} = \frac{K}{1 + \frac{1}{s}[\frac{\omega_0}{Q}] + \omega_0^2} \tag{22}$$

$$V_{hp} + \frac{1}{Q}(\frac{\omega_0}{s}V_{hp}) + \frac{\omega_0^2}{s^2}V_{hp} = KV_i \tag{23}$$

The term $\frac{\omega_0}{s}V_{hp}$ can be obtained by passing through an integrator with a time constant equal to $\frac{1}{\omega_0}$ .Passing the resulting signal through another identical integrator results third signal, involving V_{hp}, $\frac{\omega_0^2}{s^2}V_{hp}$. Figure 10 shows such two integrator circuit.

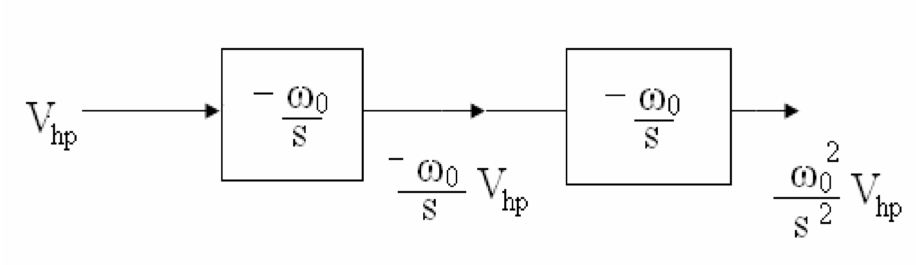
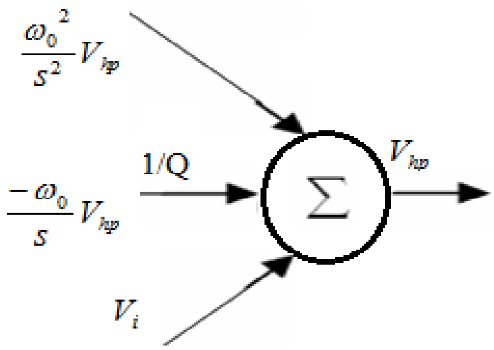


Fig.10. Integrator Circuit

In anticipation of the use of the inverting op-amp miller integrator circuit to implement each integrator, the integrator block has been assigned negative signs. V_{hp} can be obtained by rearranging the equation (23).

$$V_{hp} = KV_i - \frac{1}{Q}(\frac{\omega_0}{s}V_{hp}) - \frac{\omega_0^2}{s^2}V_{hp} \tag{24}$$

This means that Vhp can be obtained by a weighted summer.



Complete block diagram obtained by combing integral block with summer block in Fig.11.

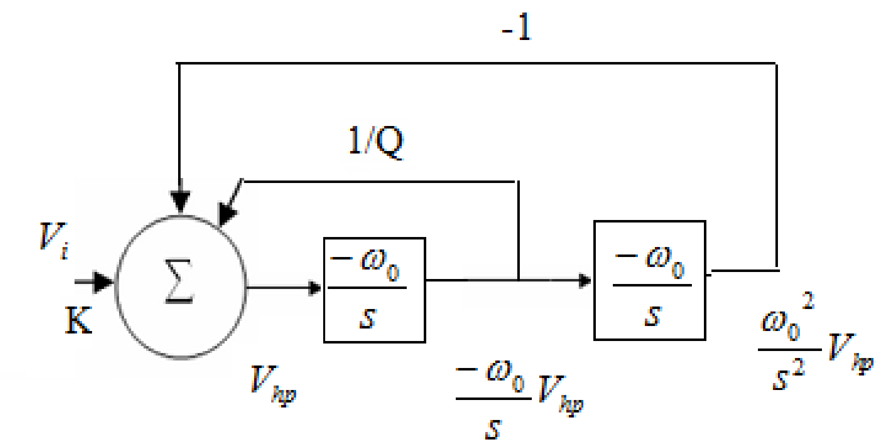


Fig.11. Blockdiagram of Biquad Filter

The high pass transfer function can be written as

$$T_{hp} = \frac{V_{hp}}{V_i} = \frac{Ks^2}{s^2 + s(\frac{\omega_0}{Q}) + \omega_0^2}$$

The signal at the output of first integrator is $-\frac{\omega_0}{s}V_{hp}$ and which is a band pass function.

$$T_{bp}(s) = \frac{-\frac{\omega_0}{s}V_{hp}}{V_i} = \frac{-K * \omega_0 * s}{s^2 + s(\frac{\omega_0}{Q}) + \omega_0^2} \tag{25}$$

The central frequency gain of band pass filter realized is equal to -KQ. The transfer function realized at the output of the second integrator is low pass function.

$$T_{lp}(s) = \frac{(\frac{\omega_0^2}{s^2})}{V_i} = \frac{K * \omega_0^2}{s^2 + (\frac{\omega_0}{Q})s + \omega_0^2} \tag{26}$$

DC gain of the low pass filter is equal to K. In biquad filter simultaneously getting high pass, low pass and band pass functions. So this circuit can be called universal filter.

Hardware test result of the biquad filter is as shown in fig.12. The input given is sinusoidal wave and the output is the fundamental component of the load current which is 90º phase shifted.

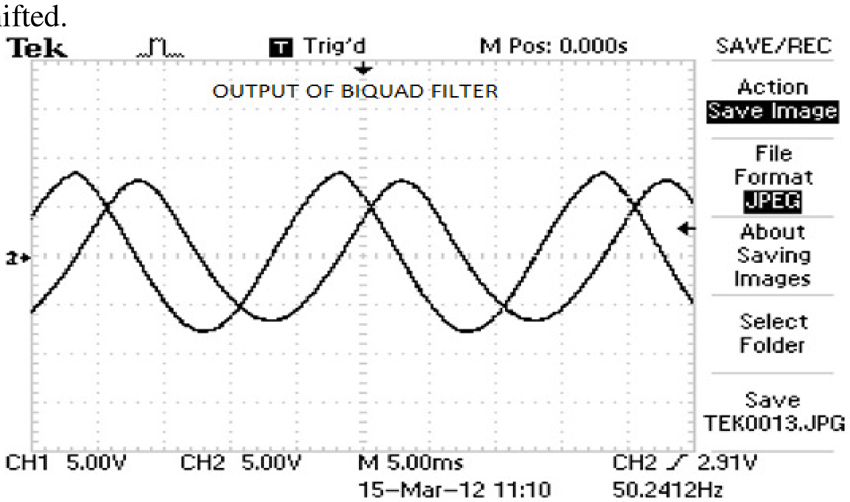


Fig. 12. Test result of biquad filter.

c. Negative Peak Detector:

This circuit involves peak detector circuit combined with 555 timer connected in monostable mode of operation. Output from the peak detector circuit is given to 555 timer to get the trigger at the negative peak of the input signal. Pulse width of the output of multivibrator is decided by the values of Rext and Cext. Fig.13. shows output of negative peak detector.

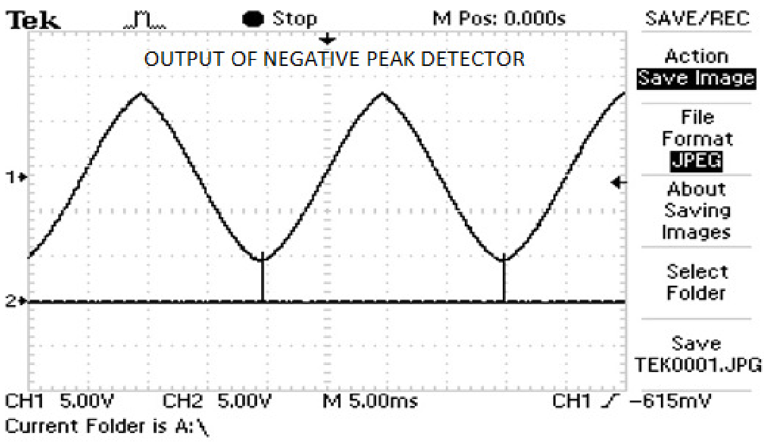


Fig. 13. Output of negative peak detector

d. Sample And Hold:

The sample and hold circuit (LF 398) gives the IsinΦ value. This has got two inputs, one is from the biquad filter and other is from monostable multivibrator. The output is IsinΦ which is getting at instant of negative of peak of the input voltage and output is given to multiplier circuit. The LF398 is a monolithic sample-and-hold circuit which utilizes high-voltage ion-implant JFET technology to obtain ultra-high DC accuracy with fast acquisition of signal and low droop rate.

e. Multiplication Circuit:

AD 633 JN is used as multiplier for multiplying IsinΦ value and unit amplitude sine wave. The output of the multiplier is the desired source current

f. The Comparator Circuit For PWM Generation:

The comparator circuit is used for producing PWM pulses for inverter. This circuit compares reference compensation current and desired source current. When reference filter current is more than actual filter current, output of the comparator is high and vice versa. The comparator is realized using op-amp 741 and IC 4049B. The 4049B is used for inverting comparator low output. Fig.14. shows output of a comparator circuit.

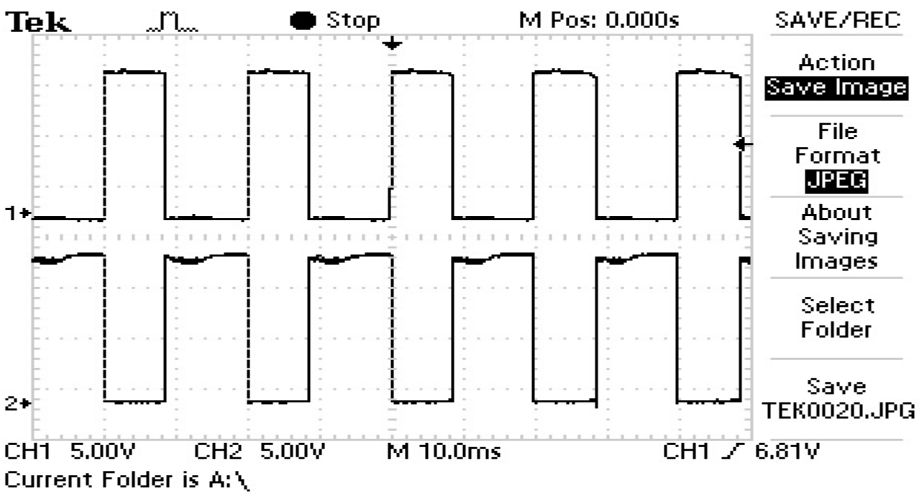


Fig. 14. PWM pulses from the hex inverter IC4049B

Fig.15. shows the experimental results – instantaneous reactive component of load current, active component of load current and load current

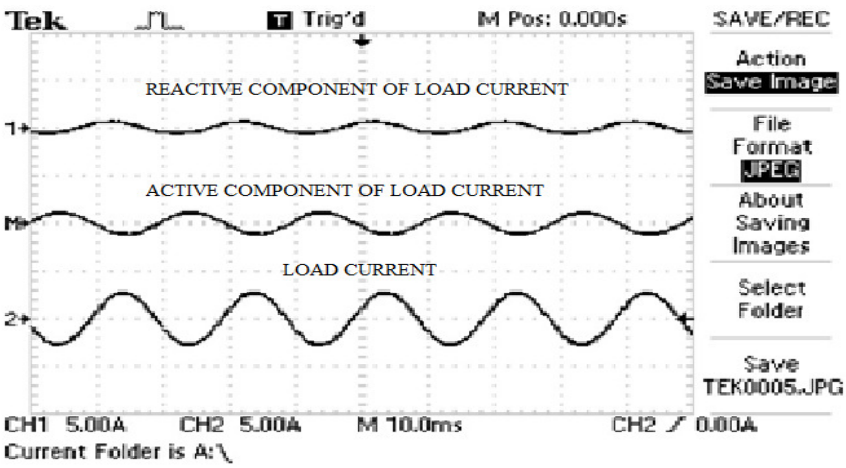


Fig. 15. Test result to extract active component from load current

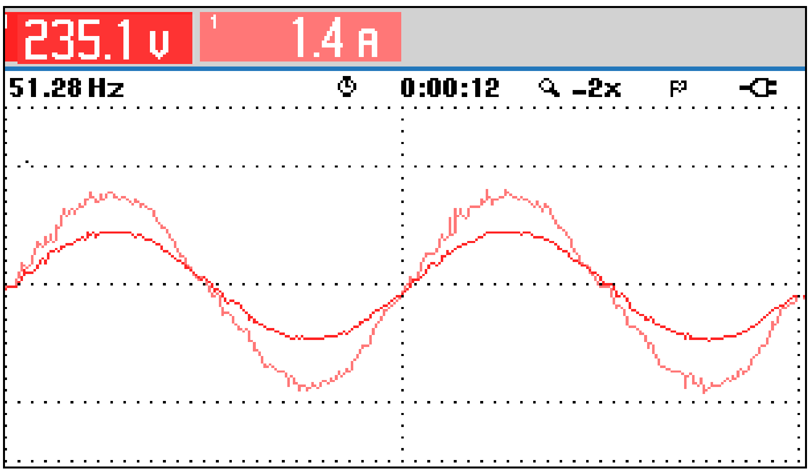


Fig. 16. source voltage and source current waveforms

Fig.16. shows source voltage and current waveforms.These two are sinusoidal and in phase which shows that effective reactive compensation is provided the proposed reactive compensator.

CONCLUSION

In this paper, a novel IsinΦ control algorithm based three phase two leg inverter is introduced to compensate three phase reactive power in induction generator. This control strategy is simple and effective when compared to other compensation techniques. The effectiveness of the control logic is verified with simulation and experimental results.

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