Role of Reactive Power Source on Power Quality of Three-Phase Self-Excited Induction Generator

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***Abstract:* -** Traditional wind turbines are equipped with induction generators. Induction generators are preferred because they are inexpensive, rugged, and require very little maintenance. Unfortunately, induction generators require reactive power from the grid to operate and/ or some capacitor compensations are often used with self excited induction generators. Static capacitors are generally employed to achieve the required performance in a self-excited induction generator. Literature survey reveals that a little work has been done to investigate the effects of capacitor bank selection on the voltage profile of generator and its effect on the harmonics generated by induction generator. In this paper an attempt is made to analyze the effects of reactive source on the performance of machine and the effects of capacitor bank on the harmonics were investigated using MATLAB/SIMULINK. Importance of capacitor bank selection on quality of output power is highlighted through simulated results as obtained.

Key words: - Induction Generators, MATLAB, Reactive Power, Self-Excitation, Wind Energy, Excitation capacitor, Harmonic Distortion.

1. Introduction

Wind power technology is known since many centuries. A machine built by Charles F. Brush in Cleveland, Ohio in 1888 produced the first wind-powered electricity. It had a rated power of 12 kW direct current. Direct current electricity production continued in the form of small scale, stand-alone (not connected to a grid) systems until the first large scale AC turbine was constructed in the USA in 1930’s. There was then a general pause in interest until the 1970's when the fuel crises sparked a revival in research and development work in USA, Canada and Europe. Modern wind turbine generators are highly sophisticated machines, taking full advantage of state-of-the-art technology, led by improvements in aerodynamic and structural design, materials technology, mechanical, electrical and control engineering and capable of producing several megawatts of electricity.

During 1980's installed capacity costs dropped considerably and wind power became an economically attractive option for commercial electricity generation. Large wind farms or wind power stations have become a common sight in many western countries. For developing countries like India, wind turbines offer an attractive source for power production. Both central and state agencies, various private and public sector companies are now considering the installation of wind farm projects for power generation.

The installed capacity of Indian Wind Power sector reached to 6,270 MW by the end of December 2006. In the past 30 years, the size of wind turbines and the size of wind power plants have increased significantly. A large increase in wind generation was witnessed in the year 2006-07 [1].

14,900 MW was added in the past year summing up to a global installed capacity of 73,904 MW by the end of December 2006. The added capacity equals a growth rate of 25 %, after 24 % in 2005. The currently installed wind power capacity generates more than 1 % of the global electricity consumption. Based on the accelerated development, WWEA has increased its prediction for 2010 and expects now

160,000 MW to be installed by the end of 2010. Five countries added more than 1000 MW: the United States of America (2,454 MW), Germany (2,194 MW), **India (1,840 MW)** and Spain (1,587 MW) were able to secure their leading market positions and China (1,145 MW) joined the group of the now top five markets and is now number five in terms of added capacity.
Induction generators are increasingly being used in wind energy generation systems for energy conversion. The advantages of using an induction generator instead of a synchronous generator are well known. These can be used in stand alone; grid connected or doubly fed modes. The advantages of using induction generators are their simple construction; no brushes, diodes, or collector rings, no synchronizing circuit for paralleling to the utility, Lower maintenance cost and large power swings do not pull the generator out of synchronization with the system [2, 3]. In the recent years SEIG's have received increased attention and they have been extensively utilized as suitable isolated power source. The same machine can be connected to the grid to work as GCIG with capacitor compensation to supply the reactive power [4, 5]. DFIG are also extensively used for power generation with the development in the power electronics.

The increase in the amount of wind power generation has surpassed the capability of the infrastructure for which it was designed. The infrastructure was built to support small, scattered wind generation. Similarly, because wind plants were so small in the past, the rules governing wind generation were more relaxed to encourage development. But as the amount of wind generation increases, the lack of rules, standards, and regulations during early wind development has proven to be an increasing threat to the stability and power quality of the interconnected grid. Power quality is the term that embraces all aspects associated with the amplitude, phase and frequency of the voltage and current wave forms existing in a power circuit. Electric utilities have the objective to deliver a sinusoidal voltage at a fairly constant magnitude and frequency through their system. Now a day the *power quality* issues gain more interest due to the loads that are increasingly sensitive to the power quality issues. The primary factor in the deterioration of the power quality is the voltage quality generated by said wind turbine generators. The large reactive current has sufficient time to create a brief increase in the voltage drop at the line side and hence lead to the disruption of the voltage quality [6, 7, and 8, 9].
Power quality issues in wind turbines are of particular interest for wind electrical generation because; the wind turbines are connected to distribution feeders rather than to transmission lines. Distribution feeders are not electrically "stiff," and are less able to deal with a fluctuating source like a wind turbine. (Stiffness refers to the ability of a feeder to maintain constant voltage during periods of high current.) Moreover, utility customers are typically located on the same distribution line, sometimes relatively close to the wind turbine(s), without intervening substations or transmission lines, the customers will be more directly exposed to power quality problems if any exists [10, 11, and 12]? The variations in output power inherent with wind turbines caused by changes in wind speed, turbulence, wind turbine switching events (e.g. starting, stopping, and switching speeds), and other phenomena have the potential to degrade the power quality of a distribution feeder. These power quality disturbances include sags, spikes, or transients in supply voltage as well as unbalanced voltages, harmonics and flicker. Obviously, not all of the disturbances are present simultaneously. Some of them may be innocent while others may have detrimental effects on smooth operation of sensitive equipment. Because wind is a time dependent and highly variable source, the power quality delivered to the grid must be within the desired limits.

In this paper an attempt is made to study the effect of variation in capacitor bank used for compensation on the voltage profile and harmonics of SEIG. Efforts are made to find out the most suitable value of capacitor for SEIG supplying constant load and operating at constant wind speed. Power system toolbox of MATLAB 7.0.4/ SIMULINK is used for simulation.

2. POWER QUALITY NORMS

Various standards related to power quality and grid connection of wind turbines are listed below:

- IEEE Standard 1159-1995 - IEEE Recommended Practice for Monitoring Electric Power Quality.
- IEC 61400-21 - Measurement and assessment of power quality characteristics of grid connected wind turbines.
- IEEE Standard 1453-2004 - IEEE Recommended Practice for Measurement and

Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems.

- IEEE Standard 1547-2003 - IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.
- IEC 61000-3-2 - Electromagnetic Compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions.

According to IEC 61400-21, 10 minute average of voltage fluctuations should be with in ±5% of its nominal value. It also suggests that the flicker emission from a single wind turbine should be determined by measurements.

According to Indian electricity grid code, All Regional constituents shall make all possible efforts to ensure that the grid frequency always remains within the 49.0 – 50.5 Hz band. All regional constituents shall make all possible efforts to ensure that the grid voltage always remains within the following operating range.

Voltage in kV (r.m.s.)

Nominal	Maximum	Minimum
400	360	420
220	200	245
132	120	145

The IEC has published a series of standards (IEC 61000-3-3, IEC 61000-3-5, IEC 61000-3-7) based on the P_{st} evaluation of flicker. IEC 61000-3-7 describes the allowable voltage fluctuations in medium voltage, high voltage, and extra high voltage electric power systems and the allowable emissions of voltage fluctuations generated by each fluctuating load connected to the electric power system.

Table-1

Category/ Subcategory	Typical Duration	Typical Voltage magnitude
Transients		
Impulsive		
Nanoseconds	< 50 nsec	
Microseconds	50 nsec – 1 ms	
Milliseconds	> 1 msec	
Oscillatory		
Low frequency	0.3-50 msec	0-4 p.u.
Medium frequency	20µsec	0-8 p.u.
High Frequency	5 µsec	0-4 p.u.
Short-duration variations		
Instantaneous		
Interruption	0.5-30 cycles	< 1 p.u.
Sag	0.5-30 cycles	0.1-0.9 p.u.
Swell	0.5-30 cycles	1.1-1.8 p.u.
Momentary		
Interruption	30 cycles-3sec	< 1 p.u.
Sag	30 cycles-3sec	0.1-0.9 p.u.
Swell	30 cycles-3sec	1.1-1.4 p.u.
Temporary		
Interruption	3sec-1min	< 1 p.u.
Sag	3sec-1min	0.1-0.9 p.u.
Swell	3sec-1min	1.1-1.2 p.u.
Long –duration variation		
Sustained Interruptions	>1min	< 1 p.u.
Under Voltages	>1min	0.1-0.9 p.u.
Over Voltages	>1min	1.1-1.2 p.u.
Voltage Unbalance	Steady state	0.5-2%
Wave form Distortion		
DC Offset	Steady state	0-0.1%
Harmonics	Steady state	0-20%
Inter-harmonics	Steady state	0-2%
Notching	Steady state	
Noise	Steady state	0-1%
Voltage fluctuations	Intermittent	0.1-7%
Power Frequency variations	< 10 sec	

3. System Description

System-1

The system consists of 480V, 60 Hz, 275-kVA, induction generators driven by wind turbine a fixed resistive customer load of 200 kW.

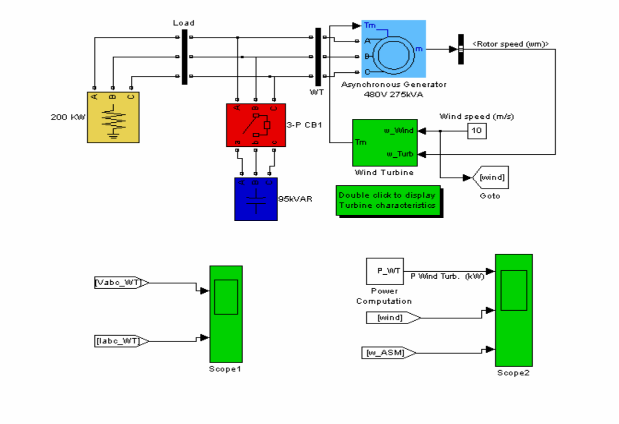


Fig. 1 System Schematic

The three-phase delta connected capacitor bank is connected at the terminals of the induction generator.

The value of this capacitor bank can be changed to study the effect on voltage profile and harmonics. The wind speed is kept constant for the study at 10 m/s. The Wind Turbine block uses a 2-D Lookup Table to compute the turbine torque output (Tm) as a function of wind speed (w_Wind) and turbine speed (w_Turb). The Pm (w_Wind, w_Turb) characteristic was automatically loaded in the workspace (psbwindgen_char array) when we open this setup. The turbine characteristics can be displayed by double click on the block located below the Wind Turbine block. The asynchronous machine operates in generator mode; its speed is slightly above the synchronous speed. According to turbine characteristics, for a 10 m/s wind speed, the turbine output power is 0.75 p.u. (206 kW).

Because of the asynchronous machine losses, the wind turbine produces 200 kW. Scope 1 is used to record the p.u. values of terminal voltage and current of the induction generator and Scope-2 records the power at the generator terminals, wind speed and the generator speed.

4. Simulation Results and Discussions

The above said system was simulated in MATLAB using the Simpower system toolbox of SIMULINK to study the effect of variation in capacitive compensation on voltage profile and harmonics. The SIMULINK model of the system is shown in fig.1. The simulation time is 30 sec. Machine parameters are given in section-5.

3.1 Case –I Capacitor bank value 55 kVAR.

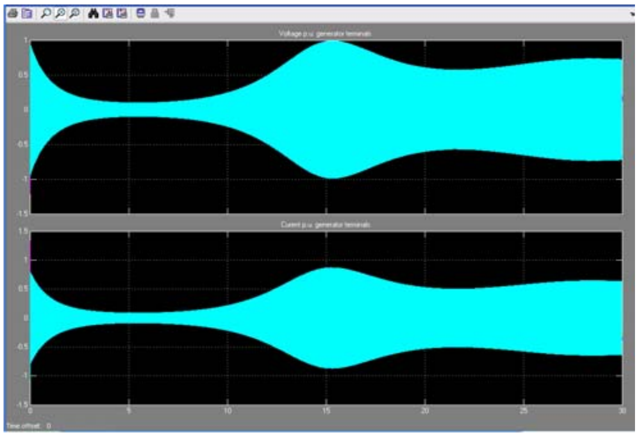


Fig. 2 Induction generator terminal voltage V_L, and line current I_L

Large variations in the voltage profile are recorded when the value of the capacitor bank at the terminal of induction generator is 55 kVAR (fig.-2). At the starting i.e. during the instant (2 sec to 9 sec) the voltage drops to very low value of 0.15 p.u. after 10 seconds the voltage started increasing and reached up to 1 p.u. momentarily then after going a low value of 0.7 p.u. it finally settles to 0.8 p.u. Similar kinds of variations are also recorded in the current. The power output is

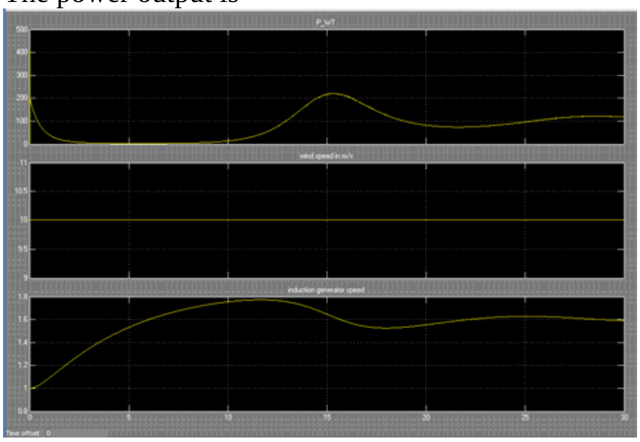


Fig. 3 Power in KW, wind speed in m/s and induction generator speed in p.u.

reduced to zero during the large dip in the voltage (fig.-3). Power reaches its max value at the instant t=15 sec reduces to a value as low as 90 kW and then finally settles to 130 kW. The wind speed is shown constant at 10 m/s. The generator speed is reached up to 1.6 p.u after variation from 1.7 p.u. at 10 sec and 1.5 p.u. at 16 sec.

3.2 Case –II Capacitor bank value 75 kVAR

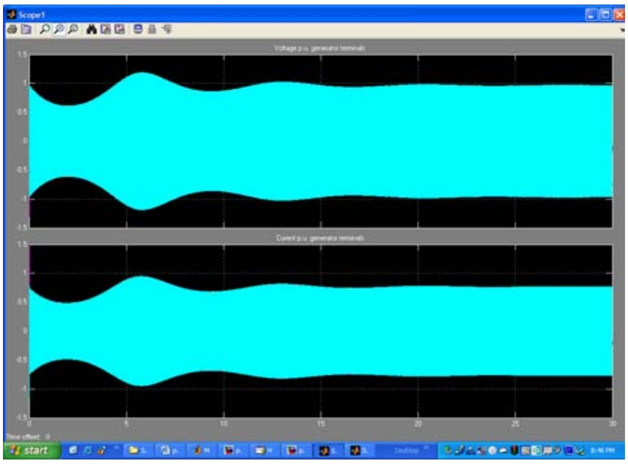


Fig. 4 Induction generator terminal voltage V_L, and line current I_L

When the value of the capacitor bank is changed to 75 kVAR the improvement in the voltage profile is seen. The duration of dip in the voltage and magnitude is reduced and becomes stable at value nearly 1 p.u. at a

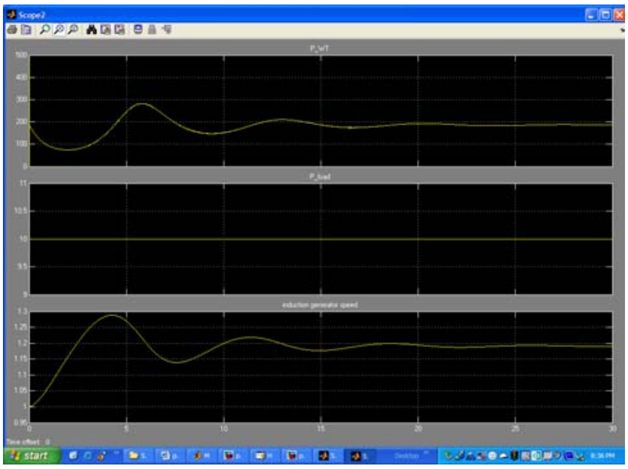


Fig. 5 Power in KW, wind speed in m/s and induction generator speed in p.u.

faster rate (fig.-4). Variations in the output power are shown in the fig.-5. A variation is from 90 kW to 290 kW and becomes steady at 195 kW. The wind speed is constant at 10 m/s. The generator speed variations are also reduced.

3.3 Case –III: Capacitor bank value 95 kVAR.

The capacitor bank value when fixed at 95 kVAR shows that the voltage profile becomes smooth (fig. 6) there are very small variations at the start and the terminal voltage is 1 p.u. Variation in the power and generator speed are very minute. With this value of capacitor the parameters under consideration i.e. voltage profile and generator speed are with in limits (fig.7).

Fig. 6 Induction generator terminal voltage V_L, and line current I_L

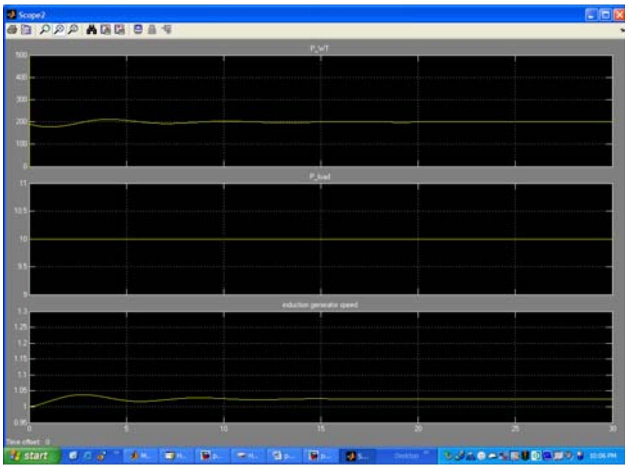
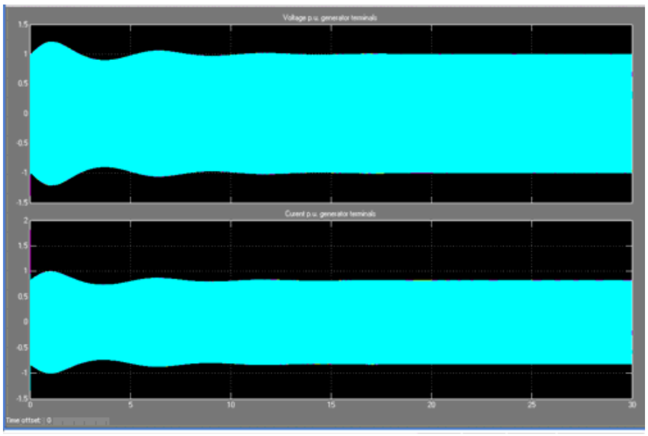


Fig. 7 Power in KW, wind speed in m/s and induction generator speed in p.u.

3.4 Case –IV Capacitor bank value 115 kVAR.

Fig 8 and Fig. 9 shows the performance of SEIG with a capacitor bank rated as 115 kVAR. An increase in the voltage is observed when the capacitor bank value is changed to 115 kVAR. The voltage rises to 1.25 p.u. and then drops back to 0.9 p.u. the decrease in the generator speed is also observed. The speed is reduced to a value of 0.9 p.u.



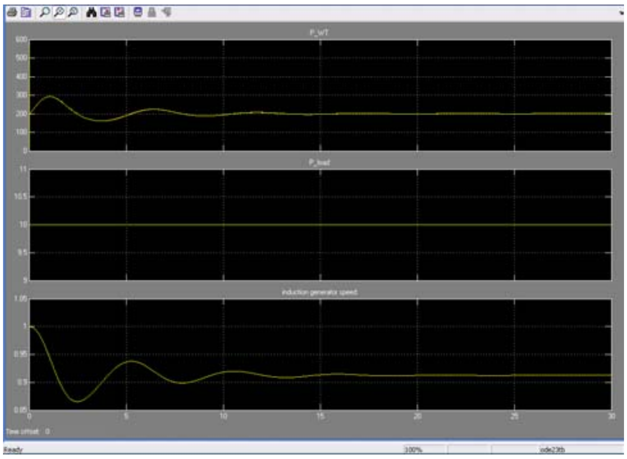


Fig. 8 Induction generator terminal voltage V_L, and line current I_L

Fig. 9 (Power in KW, wind speed in m/s and induction generator speed in p.u.)

System-2

Another system was developed to see the effect of change in capacitance (reactive power composition) on the harmonics generated by wind turbine.

The system consists 480Volts, 60Hz, 275 KVA induction generators driven by wind turbine feeding a fixed resistive customer load of 200KW. All other parameters/ components of the system are same as in system-1. In addition to that in this set-up, scope-1 is used to record per unit values of terminal voltage, current and power at generated terminals. Scope-2 records the harmonics at generator terminals. The three Fourier blocks are programmed to record 5^{th}, 9^{th} and 12^{th} harmonic at generator terminals.

Above said system was simulated in MATLAB using the SIMPOWER system tool box of simulating to study the effect of variation in capacitive compensation on the above said harmonics i.e. 5^{th}, 9^{th} and 12^{th}. Simulating model is shown in the figure-10. Simulation time is 30 seconds and the machine parameters are same used in system-1.

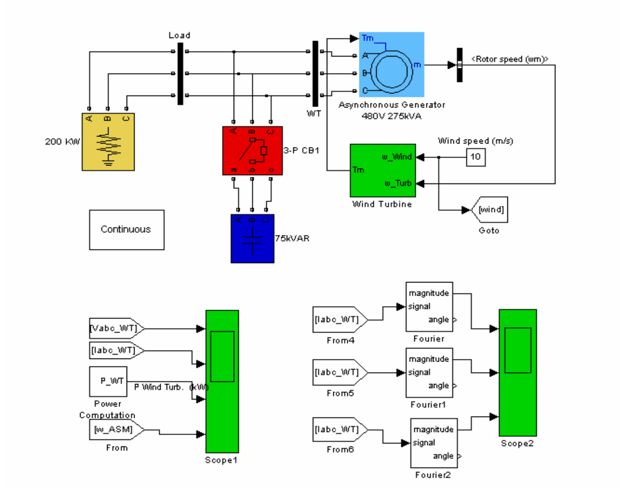


Fig. 10

The Fourier block performs a Fourier analysis of the input signal over a running window of one cycle of the fundamental frequency of the signal. The Fourier block can be programmed to calculate the magnitude and phase of the DC component, the fundamental, or any harmonic component of the input signal. Recall that a signal f(t) can be expressed by a Fourier series of the form

$$f(t) = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)......(i)$$

Where n represents the rank of the harmonics (n = 1 corresponds to the fundamental component). The magnitude and phase of the selected harmonic component are calculated by the following equations:

$$|H_n| = \sqrt{a_n^{\ 2} + b_n^{\ 2}} \text{ .... (ii)}$$

$$\angle H = a\tan\left(b_n / a_n \right) \text{ .... (iii)}$$

Where

$$a_n = \frac{2}{T} \int_{(t-T)}^{t} f(t)\cos(n\omega t)dt \text{ .... (iv)}$$

$$b_n = \frac{2}{T} \int_{(t-T)}^{t} f(t)\sin(n\omega t)dt \text{ ....(v)}$$

$$T = \frac{1}{f1} \text{ .... (vi)}$$

f_1: Fundamental frequency
As this block uses a running average window, one cycle of simulation has to be completed before the outputs give the correct magnitude and angle. The discrete version of this block allows you to specify the initial magnitude and phase of the output signal. For the first cycle of simulation the outputs are held to the values specified by the initial input parameters

3.5. Capacitor Bank Value 55kVAR

5th, 9th and 12th harmonics are seen in the output voltage and the variation is shown in the figure 11.

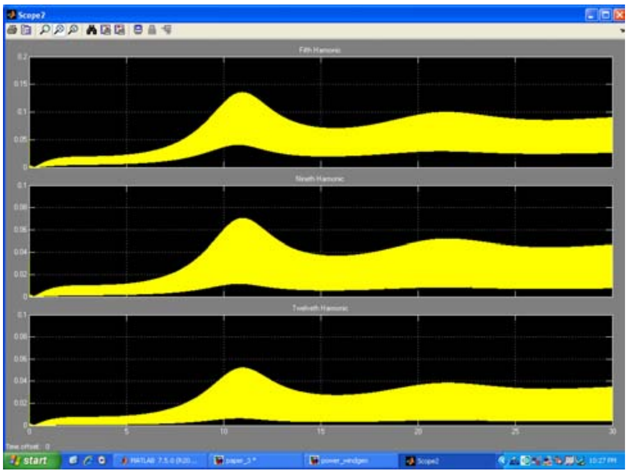


Fig. 11

It is observed that the values of 5th harmonic components are low initially, but the value rises to 0.14 near time t=12 seconds. Then drop is observed and value reaches 0.06 at t=16 and then again rises back to 0.1 at t=22 and then becomes almost steady at a value 0.09. Similar variations are recorded in 9th harmonic, which attain maximum value of 0.07 at t=12 then drops back to 0.04 at t=17 again rises back to a value of 0.05 at t=22 and after a small dip becomes steady at 0.05. 12th harmonic maximum value is 0.05 again similar kinds of variations are recorded in this also.

3.6 Capacitor Value 75 kVAR

When the capacitor value is changed to 75kVAR a reduction in 5th, 9th and 12th harmonics components was observed and it is seen that the harmonic components are varying in the similar pattern but reaches the maximum value earlier then when the capacitor value is 55 kVAR

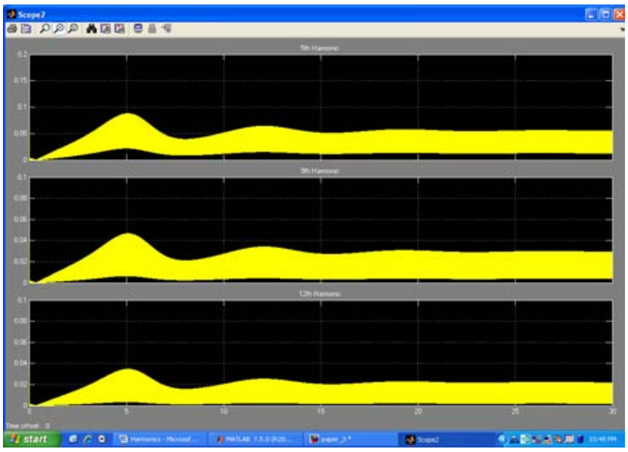


Fig. 12

3.7 Capacitor Value 95kVAR

When the capacitor value is changed to 95 kVAR a large decrease in all the harmonic components is observed and it is seen that the harmonic components are almost negligible. (Fig.-13)

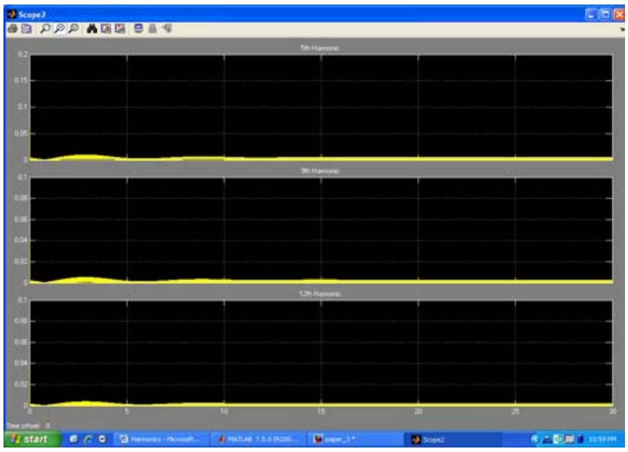


Fig.-13

3.8 Capacitor Value 115kVAR

When the capacitor value further increased to 115kVAR again and increased in harmonic components is observed.
It is seen that the maximum value reaches at about t=2 seconds and then after small variation it becomes steady. The value of 5th harmonic=0.04, 9th harmonic=0.02 and 12th harmonic=0.01.

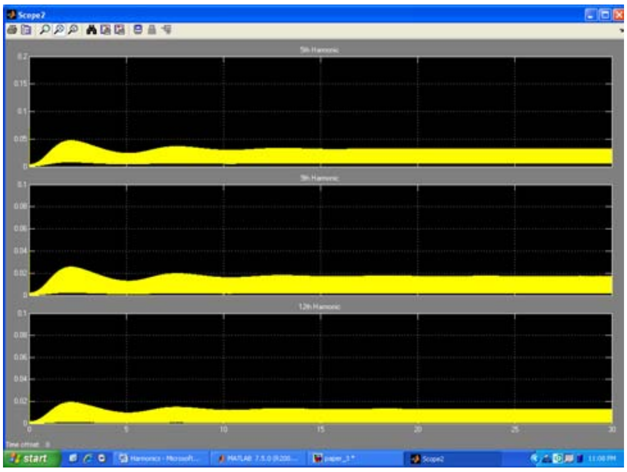


Fig. 14

4. Conclusion:

In this paper an attempt is made to use the MATLAB/SIMULINK to investigate the effects of selection of three-phase capacitor bank/reactive power source, on the performance predicting characteristics of SEIG. Simulation results as observed indicate the importance of such selection and for a specific machine (used for simulation), reactive power source with 95 kVAR gives smooth voltage profile and best results. Also it is observed that reactive power source with 95 kVAR gives lowest value of 5th, 9th and 12th harmonic. The possible source of harmonics in this setup is due to magnetic saturation of the iron core. The tap changer, the power factor, and the level of generation of the wind turbine affect the level of saturation, and thus, the nature of the harmonic source. This emphasize for the need of appropriate technique to select the optimum rating of capacitor bank that results quality output of the generator.

5. System Parameters:

5.1 Three phase induction generator:

1. Rotor type	:	Squirrel Cage
2. Reference frame	:	Rotor
3. Nominal power	:	275 KVA
4. Voltage (line-to-line)	:	480 V
5. Frequency	:	60Hz
6. Stator resistance (pu)	:	0.016
7. Stator inductance (pu)	:	0.06
8. Rotor resistance (pu)	:	0.015
9. Rotor inductance(pu)	:	0.06
10. Mutual inductance (pu)	:	3.5
11. Inertial constant	:	2
12. fraction factor	:	0
13. Pair of poles	:	2

5.2 Three Phase load:

1. Nominal power	:	200 KW
2. Voltage (line-to-line)	:	480 V
3. Frequency	:	60Hz
4. Configuration	:	Y grounded

5.3 Power factor Correction capacitors:

1. Pf correction capacitor case 1	:55kVAR
2. Pf correction capacitor case 2	:75kVAR
3. Pf correction capacitor case 3	:95kVAR
4. Pf correction capacitor case 3	:115kVAR
5. Configuration	:Delta
6. Nominal voltage	:480V
7. Frequency	:60Hz

5.4

1. Scope 1:
   - 1.1 Records the terminal voltage of induction generator.
   - 1.2 Measures the terminal current of the induction generator.
   - 1.3 Records the power at the terminals of Wind turbine.
2. Scope 2:
   - 1.1 Records the 5th harmonics.
   - 1.2 Records the 9th harmonics.
   - 1.3 Records the 12th harmonics.

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