



Advanced Power Quality Optimization in Wind Energy Conversion Systems Via Soft Computing and Pi Control Strategies for Weak Grids

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ABSTRACT

As the global shift towards renewable energy accelerates, the integration of wind power into existing electrical grids continues to rise, posing operational challenges, particularly in weak grid environments .These grids, characterized by substantial voltage and frequency variability, can compromise the performance, safety, and efficiency of wind turbines. This research investigates the deployment of Soft Computing Techniques, leveraging Proportional-Integral (PI) Controllers, to enhance power quality in wind energy conversion systems. Emphasis is placed on minimizing Total Harmonic Distortion (THD), ensuring dynamic stability, and maintaining system reliability. Through comprehensive simulations across diverse loading conditions and fluctuating wind speeds, the PI Controllers demonstrate superior precision in rotor speed and position estimation. The findings illustrate the robustness of the proposed approach, significantly improving turbine performance and grid resilience in weak electrical networks.



INTRODUCTION

The growing concern about global warming and the harmful effects of fossil-fuel emissions has created new demand for renewable energy sources. Also the global electrical energy consumption is still rising and there is a steady demand to increase the power capacity. The production, distribution and the use of the energy should be as technological efficient as possible and incentives to save energy at the end-user should be set up. The deregulation of energy has lowered the investment in larger power plants, which means the need for new electrical power sources may be very high in the near future. Two major technologies will play important roles to solve the future problems. One is to change the electrical power production sources from the conventional, fossil based energy sources to renewable energy resources. The other is to use high efficient power electronics in power systems, power production and end-user application. While fossils fuels will be the main fuels for the thermal power there is a fear that they will get exhausted eventually in next century therefore many countries are trying systems based on non-conventional and renewable sources. These are Solar, Wind, Sea, Geothermal and Biomass. Solar power on earth is 106 watts and the total world demand is 10 13 watts. If we utilize 5% of the solar energy, it will be 50 times what the world requires. If we consider the wind potential it is estimated to 1.6×10^7 MW, which is same as world energy consumption. So the development of non-conventional energy source is very economical. The most emerging renewable energy source is wind energy, with the use of power electronics which means the wind energy is changing from being a minor energy source to an important power source in the energy system. Wind turbines (WTs) can either operate at fixed speed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine the generator is controlled by power electronic equipment. Differential heating of the earth's surface by the sun causes the movement of large air masses on the surface of the earth, i.e., the wind, the power of which is converted to electricity. Hence by using this renewable source of energy power can be generated and the demand for power can be met at necessary condition, as it is a grid connected system. As energy crisis is very high in case of developing countries like India. There came urgent need to look for secondary sources of energy that are clean and pollution free, as conventional sources cause much pollution. This paved path for non-conventional sources. Of all the renewable energy sources, the one that has matured to the level of being a utility generation source is wind energy. It is estimated that wind potential is 1.6×10^7 MW which is same as world energy requirement. But the only problem is that wind speed is highly fluctuating, which gives rise to many problems during power generation. So we mainly concentrate on the problems that occur during generation and how they can be rectified. The problems faced are due to local impacts and system impacts. Local impacts deal with the impacts that occur in the vicinity of the wind turbine or wind farm. System impacts are the impacts that affect the behavior of the system as a whole. Using modern



power electronics and special type of wind turbines that suit to the conditions can solve local impacts. Designing turbines to withstand voltage variations of certain magnitudes can rectify system impacts to some extent. Controlling the rotor speed by gear mechanism can rectify problems due to high wind or computer aided techniques. Doubly-fed induction generators are commonly used for larger wind turbines. The major advantage of the doubly-fed induction generator is that the power electronic equipment has to handle only a fraction of the total system power. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator, apart from the cost saving of using a smaller converter. The power quality is a set of parameters defining the properties of the power supply as delivered to user in normal operating condition in terms of continuity of supply and characteristics of voltage and frequency. The critical power quality issues related to integration of wind farms have been identified. The power quality in relation to a wind turbine describes the electrical performance of wind energy generating system. It reflects the generation of grid interference and the influence of a wind turbine on power and voltage quality of grid. The issue of power quality is of great importance to the wind turbines. There has been an extensive growth and quick development in the exploitation of wind energy in recent years. However with rapidly varying voltage fluctuations due to the nature of wind, it is difficult to improve the power quality with simple compensator.

Advance reactive power compensators with fast control and power electronic have emerged to supersede the conventional reactive compensator. It has been suggested that today's industrial development are related with generalized use of computers, adjustable speed drives and other microelectronic loads. It also becomes an increasing concern with power quality to the end customer. The presence of harmonic and reactive power in the grid is harmful, because it will cause additional power losses and malfunction of grid component. The massive penetration of electronically controlled devices and equipments in low voltage distribution network is responsible for further worsening of power-quality problem. These problems are related to the load equipment and devices used in electric energy generation. Now a days the transmission and distribution system become more sensitive to power quality variation than those used in the past. Many new devices contain microprocessor based controls and electronics power elements that are sensitive to different types of disturbances. The wind power in the electric grid system affects the voltage quality. To assess this effect, the knowledge of about the electrical characteristic of wind turbine is needed. The electrical characteristics of wind turbine are manufacturer's specification and not site specification. This means that by having the actual parameter values for a specific wind turbine the expected impact of the wind turbine on voltage quality is important. Wind turbines and their power quality will be certified on the basis of measurements according to national or international guidelines. These certifications are an important basis for utilities to evaluate the



grid connection of wind turbines and wind farms. Soft computing techniques like neuro, neuro-PI controllers are used to improve the power quality of Wind Energy Conversion Systems by reducing the total harmonic distortion.

GENERATING SYSTEMS

A wind turbine is a complex system in which knowledge from the areas of the aerodynamics and mechanical, electrical and control engineering is applied.

For the generating system, nearly all wind turbines currently installed use either one of the following systems.

1. Squirrel cage induction generator systems
2. Doubly fed induction generator systems
3. Direct drive synchronous generator systems

which first one is a fixed speed or constant speed while others are variable speed turbine. Figure 3.7 shows the schematic diagram of a generator. It can be always be partly or fully compensated by capacitors in order to achieve a power factor close to one.

Doubly Fed Induction Generator Systems

The doubly fed induction generator based wind energy conversion system is shown in Figure .It is a variable speed turbine .In this case a back-to-back voltage source converter feeds the three-phase rotor winding. So the mechanical and electrical rotor frequencies are decoupled and the electrical stator and rotor frequency can match, independently of the mechanical rotor speed.

Operating principle of DFIG

Power flow diagram of DFIG is shown in figure. The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DFIG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage.

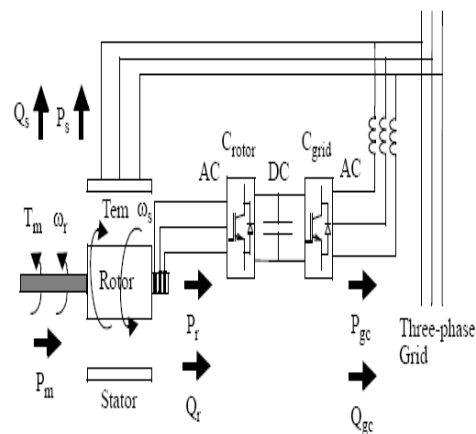


Figure Power flow diagram of DFIG

The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine. The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m \cdot r \quad (5)$$

$$P_s = T_m \cdot s \quad (6)$$

For a loss less generator the mechanical equation is:

$$J = T_m - T_m \quad (7)$$

In steady-state at fixed speed for a loss less generator

$$T_m = T_m \quad \text{and} \quad P_m = P_s + P_r \quad (8)$$

and it follows that:

$$P_r = P_m - P_s = T_m \cdot r - T_m \cdot s = -s P_s \quad (9)$$

$s = (s - r) / \omega_s$ is defined as the slip of the generator Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s . Since T_m is positive for



power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to raise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by Crotor. The phase-sequence of the AC voltage generated by Crotor is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. Crotor and C_{grid} have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

Direct Drive Synchronous Generator Systems

Figure .shows the direct drive synchronous generator systems In this case, generator is completely decoupled from the grid by a power electronics converter connected to the stator winding.

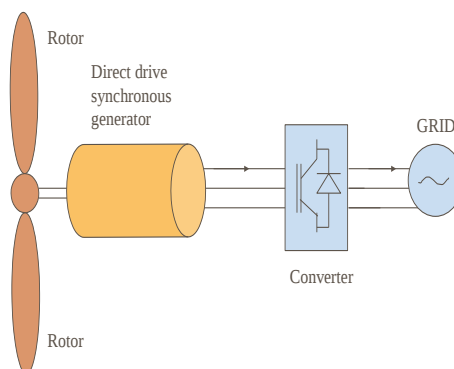


Figure . Direct drive synchronous generator systems

The direct drive generator is excited using an excitation winding or permanent magnets. But directly grid coupled synchronous generators are not used in wind turbines due to unfavorable dynamic characteristics. When used in combination with a fluctuating prime movers cause high structural loads and a risk of instability during wind gusts which is also a problem.



CONTROL STRATEGY

In power systems, large power generation plants located at adequate geographical places produce most of the power, which is then transferred towards large consumption centers over long distance transmission lines. The system control centers monitor and control the power system continuously to ensure the quality of the power, namely the frequency and voltage. Since, the maximum power is the cubic function of generator speed for a given tip speed ratio, the continuous information of generator position and speed is essentially required. For this purpose, generally shaft-mounted speed sensors are used, resulting in additional cost and complexity of the system. To alleviate the need of these sensors, several speed-estimating algorithms are introduced. However, the precise estimation of rotor position and speed is very difficult as most of these suffer because of simplified computations based on several assumptions. For the linear systems PID controllers are used which are efficient for linear systems only and hence not effective for non-linear systems. Hence for non-linear systems PI Logic System (FLS) is used, it has the disadvantage of non adaptiveness. Neuro and Neuro-PI (NF) system based position and speed estimator of DFIG has been proposed for wide range of speed operation during variable speed condition. The NF architecture has well-known advantages of modeling a highly non-linear system, as it combines the capability of PI reasoning in handling uncertainties and capability of Artificial Neural Network (ANN) in learning from process. PI Logic allows making definite decisions based on ambiguous data. ANN tries to incorporate human thinking process to solve problems without mathematically modeling. Both of these methods can be used to solve nonlinear problems. In contrast to PI logic, ANN tries to apply the thinking process in the human brain to solve problems. Hybrid intelligent systems developed using these two methods called PI Neural Network (FNN) or Neuro-PI System (NFS)) the disadvantages found in both methods can be avoided and thus an efficient output can be obtained

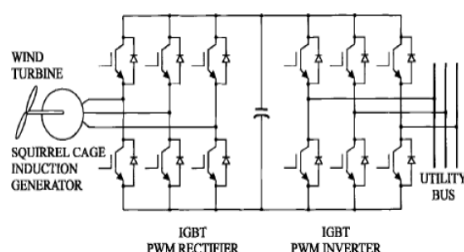


Figure. IGBT based rectifier and inverter

The voltage-fed converter scheme used in this system is shown in figure . A vertical (or horizontal) wind turbine is coupled to the shaft of a squirrel cage induction generator through a speedup gear ratio. The variable frequency variable voltage power from the generator is rectified by a PWM IGBT (Insulated Gate Bipolar Transistor) rectifier. The



rectifier also supplies the excitation need of the machine. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid. Back-to-back voltage source converter is used in doubly fed induction generator which controls the grid and rotor currents. By controlling the rotor currents by the converter it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generators turning speed. Rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power.

A salient advantage of the converter system includes the following:

- Line side power factor is unity with no harmonic current injection (satisfies IEEE 519).
- The cage type induction machine is extremely rugged, reliable, economical, and universally popular.
- Machine current is sinusoidal—no harmonic copper loss.
- Rectifier can generate programmable excitation for the machine.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine. Autonomous operation of the system is possible with either a start-up capacitor or with a battery on the dc link. Extremely fast transient response is possible. Multiple generators or multiple systems can be operated in parallel.
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available.

Considering all the above advantages, and with the present trend of decreasing converter and control cost, this type of conversion system has the potential to be universally accepted in the future. Of course, in recent years, soft-switched resonant link and resonant pole topologies have been proposed, but additional research and development are needed to bring them to the marketplace. The back to back PWM converter has two converters, one is connected to rotor side and another is connected to grid side.

Grid side converter control system

The Grid side converter is used to regulate the voltage of the DC bus capacitor and it is shown in figure 3.13. For the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage. This controller consists of

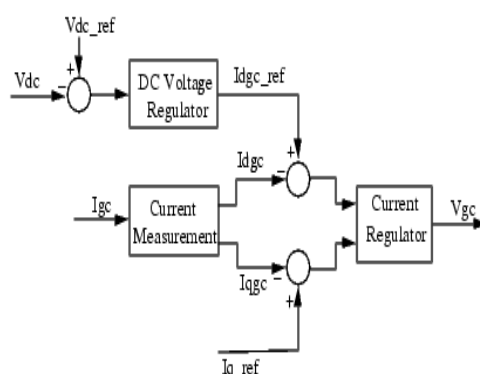


Figure . Grid side converter control

1. A measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage V_{dc} .
2. An outer regulation loop consisting of a DC voltage Regulator.
3. An inner current regulation loop consisting of a current Regulator.

The current regulatory controls the magnitude and phase of the voltage generated by converter C grid (V_{gc}) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_q ref reference. The current regulator is assisted by feed forward terms which predict the C grid output voltage.

Pitch angle control system

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. For electromagnetic transients in power systems the pitch angle control is of less interest. The wind speed should be selected such that the rotational speed is less than the speed at point D.

Simulink Model of PI Based WECS

System Quantities	Values
Nominal Power	10 MW
Nominal Voltage	575 V
Nominal Frequency	60 Hz
Stator Resistance	0.0071 Ω
Stator Inductance	0.156 H
Rotor Resistance	0.005 Ω

Rotor Inductance	0.154 H
Magnetizing Inductance	2.9 H
Pole Pairs	3
Cut-in wind speed	5 m/s
Cut-out wind speed	25 m/s

The simulink model of PI Logic controller based wind energy conversion systems diagram is shown in figure 5.2. The simulink block diagram represents the working principle of wind energy conversion system. It includes wind turbine, DFIG, interconnections, NF controller.

The output of WECS is fed to the grid connected with non-linear load. It consists of wind turbine double fed induction generator, 575 v bus Voltages, three phases step up transformer. The system is operated for variable wind speed with different loading condition.

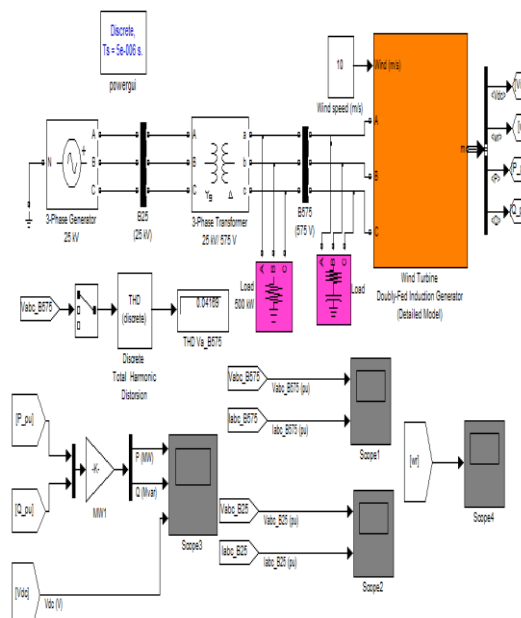


Figure . Simulink model of PI logic controller based WECS

The wind turbine specification of PI logic based wind energy conversion system is shown in table.

Table Wind turbine generator specification

The simulink model of wind turbine induction generator is shown in figure . The stator of doubly fed induction generator is directly connected to grid and the rotor is connected to grid through the back to back converter. The firing pulse for the back to back converter is controlled by using PI logic controller. The stator and rotor parameters like voltage and current, speed, position, rotor angle, wind speed, DC link voltage, Real power, reactive power is sensed and it is fed to the PI logic controller unit. The simulink model of wind turbine is shown in figure 5.4. The mode is based on wind speed and pitch angle. The motor torque is represented by T_m . All the parameters are represented by per unit.

Back to Back Converter Control System

The control system for the power converter is shown in figure 5.5. The pulse width modulation firing pulses to trigger the back to back converters is generated by using this control system. Filer circuit is used to filter the actual parameters of the system like rotor side converter output voltages, rotor side converter output currents, common link DC voltage, stator current and voltage.

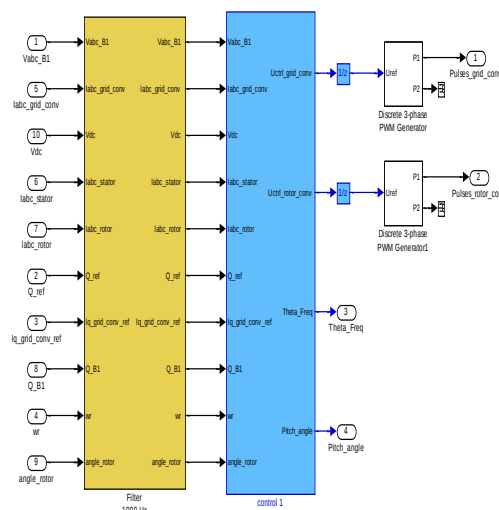


Figure Back to back converter control system

The Grid and rotor side controller circuit is shown in figure 5.6. A PI logic controller used to control the pitch angle, grid side and rotor side converters. Based on the reference and the actual values the PI logic controller generates the pulse width modulation firing pulse for the two converters.



Simulink Model for Rotor Side Converter Control

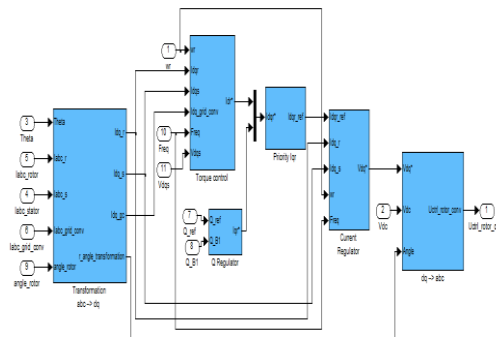


Figure . Simulink model for rotor side converter control

The simulink model of rotor side converter control is shown in figure 5.8. It consists of abc-dq transformation block, torque control, real power control, current regulator and abc - dq transformation block.

Block of DC Bus Voltage Regulator

PI logic based voltage regulator is shown in figure .The actual DC voltage is compared with the reference DC voltage and the error is fed to PI logic controller. The output of PI controller is set as reference DC current.

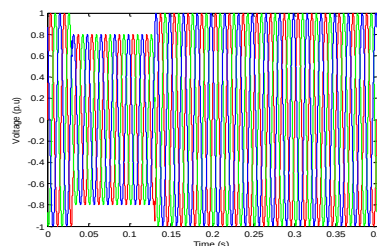


Figure . Rotor side output voltage Vs time characteristics of PI system

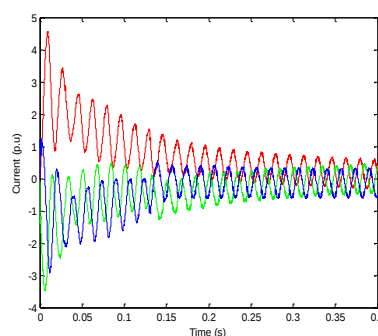


Figure . Rotor side output current Vs time characteristics of PI system



The Rotor side converter output voltage (575V) and current waveforms are shown in the figure 5.13 and 5.14. Initial disturbances present in the output will be sensed by using the PI logic control system, it will eliminate the harmonics formed in voltage side. The graph is plotted for time $t=0.4$ sec. The real power Vs time characteristics of PI logic controller based asynchronous machine is shown in figure 7.5. The real power is measured in MW.

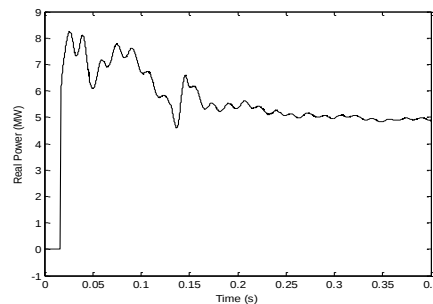


Figure . Real power Vs time characteristics of PI system

The reactive power Vs time characteristics of PI logic controller based asynchronous machine is shown in figure . In this there will be a point when the reactive power falls at zero due to harmonics present in the system. This rectification will be done by the PI logic control by eliminating the errors and producing a stable graph. The total harmonic distortion in the rotor side converter output voltage with variable wind speed and different loading condition using PI logic controller is calculated and it is tabulated in table 5.1. For a wind speed of 10 m/s and the differing conditions, the total harmonic distortion of rotor side converter output voltage ranges from 0.041 to 0.0429. For a wind speed of 15 m/s and the differing conditions, the total harmonic distortion of rotor side converter output voltage ranges from 0.043 to 0.0426. For a wind speed of 20 m/s and the differing conditions, the total harmonic distortion of rotor side converter output voltage ranges from 0.042 to 0.0428.

Table .Total harmonic distortion by using PI control system

Load	THD with wind speed of 10 m/s	THD with wind speed of 15 m/s	THD with wind speed of 20 m/s
100 Kw	0.0429	0.0426	0.0428
200 kW	0.0425	0.0423	0.0424
300 kW	0.0421	0.0421	0.0420
400 kW	0.0417	0.0420	0.0418
500 kW	0.0416	0.0414	0.0415



600 kW	0.0414	0.0412	0.0412
700 kW	0.0409	0.0410	0.0409
800 kW	0.0406	0.0406	0.0405
900 kW	0.0405	0.0405	0.0404
1000 kW	0.0401	0.0403	0.0402

CONCLUSION

Wind power penetration is increased day by day. The integration of high penetration level of wind power into existing power system has a significant impact on the power system operation. The wind turbines connected with weak grids have an important influence on power system. The weak grid is characterized by large voltage and frequency variations, which affect the wind turbines regarding their power performance, safety and allied electrical components. The strength of the distribution system is important from the point of power quality. Soft Computing Techniques are the most rapidly advancing techniques in the field of research especially, in technological advances in wind energy conversion systems. In this thesis, Soft Computing Techniques like PI Controllers are used to enhance the power quality by reducing the Total Harmonic Distortion. The simulation results have been provided under different loading conditions and variable wind speed operation. The PI estimators are able to estimate the rotor speed and position accurately under both steady-state and dynamic conditions.

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