VOL. 2. NO. 2
ISSN 2581-5849
UGC APPROVED JOURNAL: NO. 63922

PDPU JOURNAL OF ENERGY AND MANAGEMENT

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Gandhinagar, Gujarat, India

PDPU JOURNAL OF ENERGY AND MANAGEMENT

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PDPU JEM shall be published biannually.
All editorial correspondence should be addressed to the Chief Editor, C. Gopalkrishnan, School of Petroleum Management, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat - 382007 or sent by mail to *jem.pdpu@pdpu.ac.in*.

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PUBLISHER'S DETAILS:
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Gandhinagar, Gujarat - 382007, India.

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CONTENT

EDITORIAL

We are very happy to present to you this edition of Journal of Energy and Management. The following are the highlights of the papers presented in the journal.

"Electricity Generation Potential of Rooftop Photovoltaics in Punjab" by R.K. Pal discuses the potential of Solar Energy in Punjab. This study estimates the potential of solar electricity generation in the state by installing rooftop photovoltaics on residential houses. It was estimated that around 2475 GWh/year can be generated from rooftop solar photovoltaics installed on 90% of the residential houses in Punjab, which, it is estimated could meet the demand to the extent of 25 per cent of the requirements in the state today. Money savings are also realizable in case of rooftop photovoltaics. The total money savings for rooftop photovoltaics will be about Rs. 14850 Million/year. Reduction in greenhouse gases emission is also possible by using rooftop photovoltaics. The reduction in emission of greenhouse gases like carbon dioxide, methane and nitrous oxide would be about 806.67 kT/year, 92.9 kT/year and 13.51 kT/year respectively.

The second paper by Devang Parmer and Chirag Vibhakar reports findings of their study "Power Converter Topology of Brushless DC Motor for Improvement of Power Quality." This study examines different control schemes and design related power factor improvement techniques used for brushless DC motor drives. It also provides a base for a range of a suitable power factor correction topology for the specified application. Several AC-DC Buck, Boost, Cuk converters based power factor correction typologies are designed, modeled and analyzed. Portions of the bi-directional extension converter and unipolar inverter typologies are likewise surveyed to give a total evaluation of the power factor controller topologies for BLDC drives. The proposed power factor correction converter topologies indicate modification to worldwide power quality measures with an enhanced implementation of BLDC drives. It also conforms to international power quality standards with improved performance of BLDCM drive, such as reduction of AC mains current harmonics, near unity power factor, and reduction of speed and torque ripples. Simulation environment with PSIM version 9.0.3.400 software has also been attempted in the study.

The third paper, "Design Parameters of Shunt Active Filter for Harmonics Current Mitigation" by A.H. Budhrani, K.J. Bhayani, A.R. Pathak, discusses design parameters of three phase shunt active filter based on PQ theory for mitigation of harmonics current.

A Framework for Development of Risk Severity through the Application of Fuzzy Expected Value Method (FEVM) for Infrastructure Transportation Project by Manvinder Singh, Debasis Sarkar examines risks and risk assessment aspects and finally risk mitigation measures based on the analysis of mega Infrastructure transportation projects using Fuzzy Expected Value Method (FEVM).Fuzzy logic is incorporated within conventional Expected Value Method (EVM) to map the interrelationship between probability of occurrence and impact generated for a particular activity. Based upon fuzzy risk severity values, ithas been concluded that erection of pre-cast segments, detailed project report and feasibility, land handing over, traffic diversion and piling activities are having very high fuzzy risk severity values and came under first five ranks with respect to risk involved and associated with them. The developed fuzzy risk severity values would enable the project authorities to identify the activities with high risk severity and to take the mitigation measures accordingly.

The last paper of the journal is about fault detection and diagnosis methods in power generation plants specifically from the Indian power generation sector perspective by Himanshukumar R. Patel and Vipul A. Shah. The paper discusses about different faults related to nuclear power plants, thermal power plants, and solar power plants and their performance monitoring, instrumentation or sensor calibration, system dynamics, system faults, sensor faults, equipment monitoring, reactor and furnace monitoring, and transient monitoring. The authors suggested for a model-based and model-free FDD methods and examined the FDD methods. The paper explained about the popularity of FDD applications as safety and reliability are significant requirements for different power generation sector. The paper also discussed the model based and model-free FDD methods in nuclear power plants, thermal power plants, and solar power plant types of power generation plants.

We would like to receive feedback from our readers and authors, which, we hope, will help us to improve our journal.

- C. Gopalkrishnan, Chief Editor

1

ELECTRICITY GENERATION POTENTIAL OF ROOFTOP PHOTOVOLTAICS IN PUNJAB

R K Pal

ABSTRACT: Solar energy is pollution free and is available in Punjab for around 300 days in a year. Installing photovoltaics on rooftops can solve the need for open land required for solar photovoltaics. An estimate of the potential of solar electricity generation in the state by installing rooftop photovoltaics on residential houses was carried out in this study and it was estimated that around 2475 GWh/year can be generated from rooftop solar photovoltaics installed on 90% of the residential houses in Punjab. The electricity produced by solar photovoltaics installed on rooftops of 90% of the houses can supply upto 25% of the total domestic electricity needs in the state. Money savings are also realizable in case of rooftop photovoltaics. The total money savings for rooftop photovoltaics mounted on 90% of the houses would be about 14850 Million/year. Reduction in greenhouse gases emission is also possible by using rooftop photovoltaics. The reduction in emission of greenhouse gases like carbon dioxide, methane and nitrous oxide would be about 806.67 kT/year, 92.9 kT/year and 13.51 kT/year respectively. So rooftop photovoltaics can be used to reduce the emission and are economical over their full life span.

KEYWORDS

Renewable energy, solar energy, photovoltaic cell, solar electricity

Introduction

Urbanization is expected to continue at a faster rate in the near future (UN, 2014), as a result of which expenditure on energy is anticipated to increase rapidly (Pal, 2015). At present, the main source of energy supply is from fossil fuels. However, combustion of fossil fuels produces a lot of greenhouse gases with undesirable consequences (Peng & Lu, 2013). Electricity is the most convenient source of energy used and among the user categories, domestic sector is one of the major consumers of electricity. Coal based thermal power plants generate a major share of total power in Punjab. The high percentage of the total power generation from coal produces a lot of greenhouse gases. On the other hand Punjab has vast potential of solar energy with over 300 days of sunshine in a year (Anon., 2012). Annual average global insolation in Punjab is nearly 5.25 kWh/m2 in a day (Ramachandra et al, 2011). Therefore the problem of greenhouse gas emission can be reduced by using solar energy for generating electricity. Photovoltaics can be used to generate power from solar energy. These are environment friendly and have a huge potential for sustainable source of electricity generation (Hosenuzzaman et al, 2015). Photovoltaic manufacturing cost is decreasing due to increase in production (Lang et al, 2016). The payback time period is around 3 years only for the photovoltaic systems (Hosenuzzaman et al, 2015). Electricity generated from photovoltaics will be competitive with traditional systems very soon and will be an ideal source of renewable energy (Peng & Lu, 2013). The cost of photovoltaic modules in India is around Rs. 4.95 crores/MW (Anon., 2017). The problem, however, is that Photovoltaic plants require around 2.13 ha of land per MW of electricity generated (Chandel et al, 2014). Acquiring this large land area is not an easy job in any state (Sukhatme, 2011). So, the real obstacle is accessibility of open land and not the setup costs in the near future or in the long run (Sukhatme, 2011). Therefore, the potential for generating electrical power through solar photovoltaic power plants may be limited, if we depend upon availability of open land. However, the problem of open land availability is not insurmountable and can be solved by installing solar photovoltaics on rooftops (Pal, 2012 and Peng & Lu, 2013). Therefore the use of rooftop photovoltaic cells is the viable option to utilize the available solar energy. Around 30% of the annual electricity can be generated by rooftop photovoltaics (Byrne et al, 2015). Further the greenhouse gas emission can be reduced by utilizing rooftop photovoltaics (Peng & Lu, 2013). Also there are no transmission and distribution losses because the electricity is produced on-site (Ruther et al, 2008).

Keeping in mind that the domestic sector is one of the major consumers of electricity and rooftop photovoltaics can be used to generate electricity from solar energy in an environment friendly way, an attempt is made here to estimate the potential of solar electricity generation by installing photovoltaic cells on the rooftops of the houses in Punjab.

Materials and Methods

Various materials and methods used for the present work to compute the parameters like electricity generated, monetary savings, and greenhosue gases emission reduction are presented in the following sections.

Materials

Solar thermal or solar photovoltaic power plants can be utilized to generate electricity from solar energy. In solar thermal power plants, high pressure steam is produced by focusing the sun's energy. The steam produced can be utilized for generation of electricity. The main hurdle in this is requirement of open land. The open land requirement for solar thermal power generation is around 3 ha/MW of electric energy produced (Sharma et al, 2015). Conversion via photovoltaic method is another way of generating electricity from solar energy. Solar photovoltaics cells can give 25 to 30 years of functional life (Granata et al, 2014). The problem of acquiring open land exists in case of solar photovoltaics power plant also. The problem of availability of open land can be solved by using rooftops photovoltaic cells on the residential buildings (Pal, 2012 and Peng & Lu, 2013). The photovoltaic cells based on the photovoltaic effect can generate electric current or voltage in a material on exposure to light. In photovoltaic effect the electrons gets transferred between different bands within the material thereby developing potential difference between the two electrodes. The schematic sketch of a p-n junction photovoltaic cell is shown in Fig. 1(Pal, 2012).

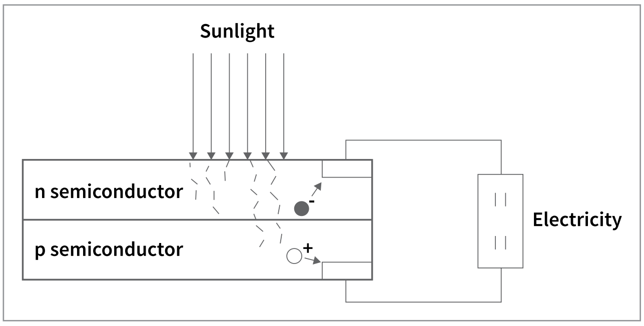

FIGURE 1. Schematics of a photovoltaic cell

The ground area to rooftop area factor can be used to find out the total available roof area (Defaix et al, 2012). The rooftop area suitable for photovoltaics installation is around 0.4 times the ground area for residential buildings (Peng & Lu, 2013). So, the available rooftop area was worked out from the roof area factor and the ground area. The electricity generation potential using rooftop photovoltaics was computed from the rooftop area available. The annual money savings are calculated from electricity generated and cost of electric energy after the payback period of the photovoltaics. The emission of greenhouse gases was computed from the electricity generated and emission factor for various greenhouse gases like carbon dioxide, methane and nitrous oxide for coal based thermal power plants.

Methods

Various methods utilized to compute the parameters like the amount of electricity generated, money savings and greenhouse gases emission reduction are presented in the following sections.

Electricity Generation

The estimation of solar electricity produced by mounting solar photovoltaic cells on rooftops of houses in Punjab is based on Eq. (1) (Pal, 2012) given below: -

$$P = L * p * n * N_{pv} * h \quad (1)$$

Where P is total power generated (in GWh/year), p is power generated by rooftop photovoltaic per house (0.4 kW), L is load factor of cell/year (0.2) (Sukhatme, 2011), N_{pv} is photovoltaics installed houses (%age), n is number of residential houses in Punjab (3922108) (Anon., 2011) and h is number of hours/year (8760).

Maximum 90% of residential houses are considered fit for installation of photovoltaic cells due to constraints like monetary condition of the possessor of house and strength of the house etc.

Money Savings

Money savings are obtainable by using rooftop photovoltaics after the payback period. Money savings can be computed from the total electricity generation by Eq. (2).

$$M = P * R \quad (2)$$

Where M is total money savings (Rs/year) and R is cost of electric energy (Rs/kWh).

Emission Reduction

The methods to calculate the reduction in emission of greenhouse gases like carbon dioxide, methane and nitrous oxide are given in the subsequent sections.

1. Reduction In Carbon Dioxide

The formula for computing carbon dioxide emission reduction is presented in Eq. (3). The emission reduction is worked out from product of carbon dioxide emission factor and electric energy generated.

$$M_{co2} = C_{co2} * P \quad (3)$$

Where C_{co2} is emission factor of carbon dioxide (kg/kWh), and M_{co2} is reduction in carbon dioxide (kg).

2. Reduction in Methane

The method for calculating methane emission reduction is given by Eq. (4). The methane emission reduction is figured out from the product of methane emission factor and electric energy generated.

$$M_{ch4} = C_{ch4} * P \quad (4)$$

Where C_{ch4} is emission factor of methane (kg/kWh) and M_{ch4} is reduction in methane emission (g).

3. Reduction in Nitrous Oxide

The formula for working out nitrous oxide emission reduction is given by Eq. (5). The nitrous oxide emission reduction is computed by the product of nitrous oxide emission factor and electric energy generated.

$$M_{N2O} = C_{N2O} * P \quad (4)$$

Where C_{N2O} is emission factor of nitrous oxide (kg/kWh) and M_{N2O} is reduction in nitrous oxide emission (g).

Results and Discussion

The various results like electricity generation, money savings and reduction in emission of greenhouse gases computed from Eqs. (1) – (5) are presented in the following sections.

Electricity Generation

The potential of electricity generated by installing rooftop solar photovoltaics on houses is given in Fig. 2 and Table 1. Electricity generation capacity due to rooftop solar photovoltaics installed on 10% of houses is 275 GWh/year. The electricity generation potential increases linearly with increase in percentage of houses installed with rooftop photovoltaics.

Electricity generation capacity by installing rooftop solar photovoltaics on 90% of houses in Punjab can be of the order of 2475 GWh/year. This electric energy generated can meet about 25% of total electric energy needed for domestic sector. This is a big amount considering that Punjab is a wealthy state of India and per capita energy consumption is very high as compared to some of the other states in the country. The energy consumption in Punjab on per capita basis was 1858 kWh as compared to national average of 1010 kWh in 2014-15 (Swain, 2017).

Houses with Photovoltaics	Electricity generation (GWh/year)	Money savings (Million Rs/year)	Carbon dioxide reduction (kT/year)	Methane reduction (kT/year)	Nitrous oxide reduction (kT/year)
10%	275	1650	89.63	10.32	1.5
20%	550	3300	179.26	20.64	3.0
30%	825	4950	268.89	30.97	4.5
40%	1100	6600	358.52	41.29	6.01
50%	1375	8250	448.15	51.61	7.51
60%	1650	9900	537.78	61.93	9.01
70%	1925	11550	627.41	72.25	10.51
80%	2200	13200	717.04	82.57	12.01
90%	2475	14850	806.67	92.9	13.51

TABLE 1. Electricity generation, money savings and emission reduction by rooftop photovoltaics

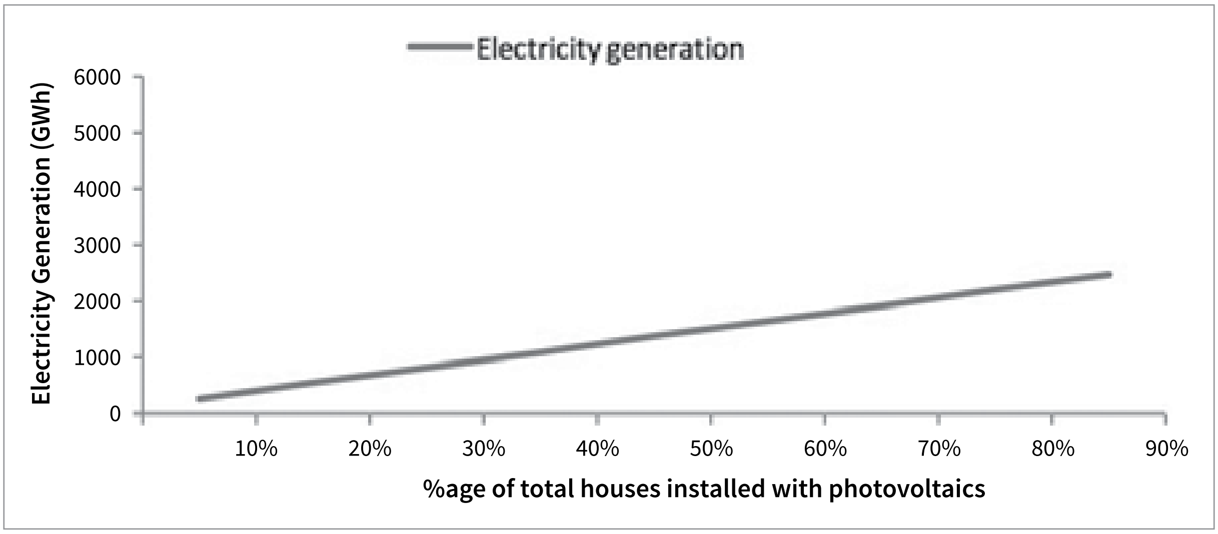

FIGURE 2. Electricity generation by using rooftop photovoltaics

Money Savings

Money savings are attainable by using rooftop photovoltaics after the payback period as there is no running cost for the photovoltaic system. The money savings obtained are presented in Fig. 3 and Table 1. The money savings obtainable by mounting rooftop photovoltaics on 10% of the houses are Rs 1650 Million/year. The money savings potential increases linearly with increase in percentage of houses installed with rooftop photovoltaics. The potential amount of money savings achievable by installing rooftop photovoltaics on 90% of the houses are Rs 14850 Million/year.

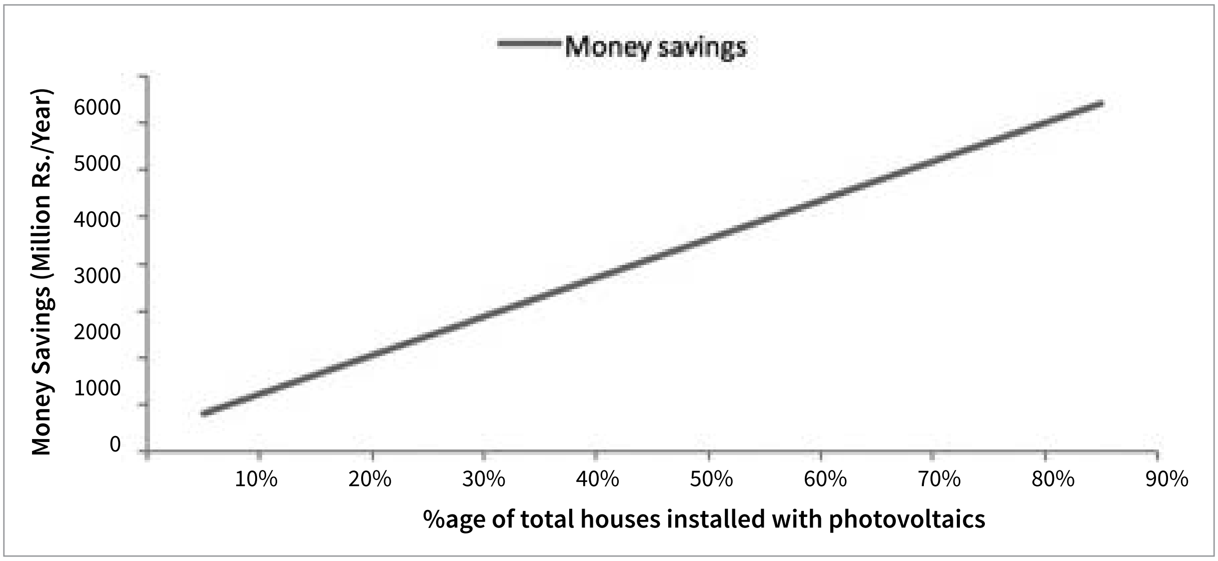

FIGURE 3. Money savings by using rooftop photovoltaics

Emission Reduction

The greenhouse gases emission reduction by installing rooftop photovoltaics on the houses in Punjab is presented in Table 1 and Fig. 4-5. The emission of these gases will get reduced due to the fact that lesser amount of electricity needs to be generated from coal based thermal power plants.

1. Carbon Dioxide Reduction

The reduction in carbon dioxide emission is possible because of electricity generation using rooftop photovoltaics. This is due to the fact that electricity generation from rooftop photovoltaics is pollution free. The reduction in carbon dioxide emission (Table 1 and Fig. 4) for Punjab is 806.67 kT/year when 90% of the houses are installed with roof top photovoltaics.

2. Methane Reduction

Reduction in methane emission is also achievable due to electricity generation using rooftop photovoltaics. This is because of the fact that electricity generated from rooftop photovoltaics is free from pollution. Total reduction in methane emission (Table 1 and Fig. 5) for Punjab is 92.9 kT/year when rooftops photovoltaics are fitted on 90% of the houses. This is significant as the global warming potential is higher for methane as compared to carbon dioxide.

3. Nitrous Oxide Reduction

Reduction in nitrous oxide emission is also attainable as a result of electricity generation from rooftop photovoltaics due to the fact already explained. Reduction in methane emission (Table 1 and Fig. 5) is 13.51 kT/year when rooftops photovoltaics are mounted on 90% of the houses. This is also significant as the global warming potential is even higher for the nitrous oxide as compared to methane.

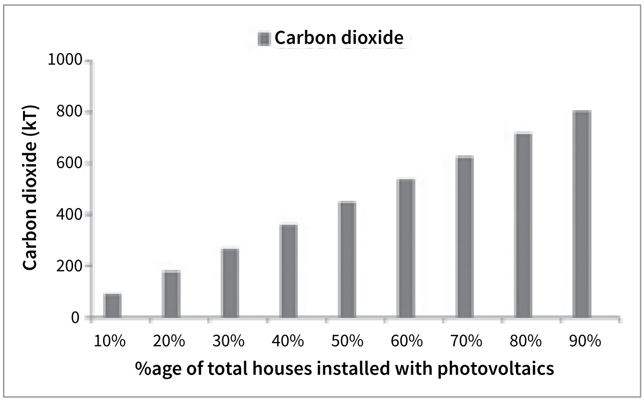

FIGURE 4. Carbon dioxide reduction by rooftop photovoltaics

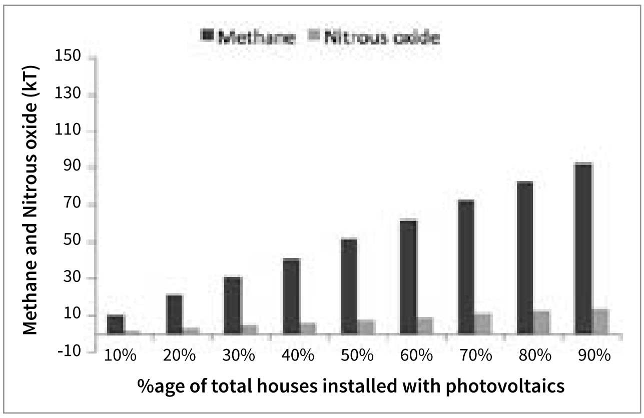

FIGURE 5. Methane & nitrous oxide reduction by rooftop photovoltaics

Conclusion

Electricity generation capacity due to rooftop solar photovoltaic cells installed on 90% of houses in Punjab can be as high as 2475 GWh/year. Rooftop solar photovoltaic cells can supply around 25% of total energy needed in the domestic sector. Money savings are also achievable after the payback period in case of rooftop photovoltaics. The total money savings for rooftop photovoltaics installed on 90% of the houses is Rs 14850 Million/year. Greenhouse gases emission reduction is also possible by using rooftop photovoltaics. The reduction in emission of carbon dioxide, methane and nitrous oxide is 806.67 kT/year, 92.9 kT/year and 13.51 kT/year respectively. Therefore, rooftop photovoltaics can reduce the emission and are more economical over the life span of the photovoltaics.

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2

POWER CONVERTER TOPOLOGY OF BRUSHLESS DC MOTOR FOR IMPROVEMENT OF POWER QUALITY

Mr. Devang. B. Parmar, Dr. Chirag. K. Vibhakar

ABSTRACT: This study signifies different control schemes and design related power factor improvement technique used for brushless DC motor drives. It alsoprovides a base for a range of a suitable power factor correction topology for the specified application. Several AC-DC Buck, Boost, Cuk converters based power factor correction typologies are designed, modeled and analyzed to a 1.5 kW BLDC drive for the comparison of performance. Portions of the bi-directional extension converter and unipolar inverter typologies are likewise surveyed to give a total evaluation of the power factor controller topologies for BLDC drives. The proposed power factor correction converter topologies indicate modification to worldwide power quality measures with an enhanced implementation of BLDC drives. It alsoconforms to international power quality standards with improved performance of BLDCM drive, such as reduction of AC mains current harmonics, near unity power factor , and reduction of speed and torque ripples. Simulation environment with PSIM version 9.0.3.400 software has also been attempted.

KEYWORDS

Brushless direct current, Voltage source inverter, Total harmonic distortion, Power factor correction, Permanent magnet brushless DC motor

Introduction

Brushless direct current motor (BLDC), a special purpose design motor, is used in industries such as electrical device, manufacturing, automation equipment, instrumentation, automotive, aerospace, medical equipment, defense applications such as vehicle tracking, gyroscope, aircraft on board instrumentation, valves, fuel monitoring system and electric actuators because of their high efficiency, high starting torque, reliability, and lower maintenance compared to its brushed dc motor. (Karthikeyan, & DhanaSekaran, 2011). BLDC motor is electronically commutated motor and does not use of brushes for commutation. There are a few points of importance in BLDC motor compared with Brushed DC motor and Induction motor, i.e. higher speed torque characteristics, high dynamic response, higher efficiency, noiseless smooth operation, and long operating life. It needs low maintenance cost. With closed-loop speed control, it is controlled in high-speed ranges. High reliability of BLDC motors compare with other energy efficient motors. BLDC motor has wide application ranging from fraction to several horsepower. They are used in automobiles and washers to raise and lower windows, drive blowers in the heaters, and air conditioners in computer drives etc. Millions of such motors are used as toy motors all over the world.

There are three types of permanent magnet materials used for BLDC motors. Alnicos are used in low-current, and high voltage applications because of low coercive magnetizing intensity and high residual flux density. Ferrites are used in cost-sensitive applications such as air conditioners, compressors, and refrigerators. Rare-earth magnets, made of samarium cobalt, neodymium-ion-boron, have high residual flux and high coercive magnetizing intensity.

Construction of Brushless DC Motors

BLDC is of two types: one is outer rotor motor, and other is inner rotor motor. The fundamental difference between the two is only in design; their working principles are same. In an inner rotor design, the rotor is positioned in the center of the motor, and the stator winding encloses the rotor. As the rotor is positioned in the core, a rotor magnet does not insulate heat inside, and heat gets dissipated easily. Due to this, inner rotor designed motor produces a large amount of torque. In outer rotor design, the rotor surrounds the winding which is located in the core of the motor. The magnets in the rotor trap the heat of the motor inside and does not allow to dissipate from the motor. Such type of motor operates at lower rated current and has low clogging torque.

Brushes are commutated with the help of armature current. This eliminates the problem accompanying with commutator segment sparking and wearing out at the brush(Shivaraj & Jayakumar, 2014).

BLDC Motor Modelling

For the speed control of BLDC motor, modelling is the required. Each of the components of BLDC drive can be modeled by mathematical equations and the combination of such models distinguish the complete BLDC drive.

The modeling of a speed controller is of prime significance as the performance of the system is contingent on this controller. If at k^{th} instantaneous of the periodic interval, $\omega_r^*(k)$ is the reference speed, $\omega_r(k)$ is the actual rotor speed than the speed error $\omega_e(k)$ can be calculated as:

$$\omega_e(k) = \omega_r^*(k) - \omega_r(k) \quad (1)$$

This speed error is processed through a speed controller to take desired control signal.(Singh & Singh, 2010).

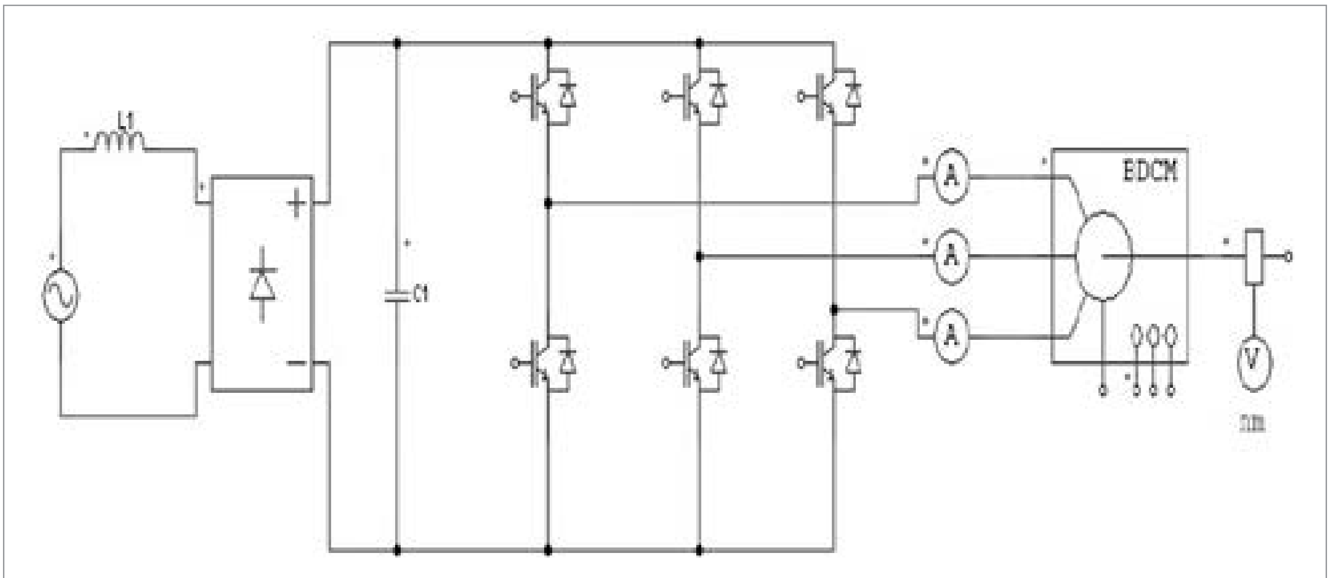

FIGURE 1. Block Diagram of Single Phase Diode Bridge Rectifier fed VSI Inverter based BLDC Motor drive

Subsequently, the flux remains constant; the speed of a BLDC motor cannot be controlled by using flux control method. The speed control and torque control of BLDC motor can be controlled by armature voltage control, armature rheostat control, and chopper control.The motor cannot be functional beyond the base speed.

Speed Controller

There can be many categories of speed controllers, for example, PI, sliding mode, Fuzzy pre-Compensated PI, Hybrid Fuzzy Proportional Integral (PI), Neural network based and Neuro-fuzzy, etc. The Proportional integral controller is the simplest and most generally used controller. For controlling drives, Proportional Integral controller output at k^{th} instant T (k) is given as,

$$T(k) = T(k-1) + K_P\{\omega_e(k) - \omega_e(k-1)\} + K_I\omega_e(k) \quad (2)$$

In above torque equation, K_P and K_I are the proportional and integral gains of the Proportional Integral controller respectively. Let I*= T(k)/K_b, where K_b is the back EMF constant of the motor.(Singh & Singh, 2010).

Reference current generation

The reference three phase currents of the motor winding are denoted by i_a, i_b, i_c for phases a, b, c, respectively. For the duration of 0 to 60 degrees, the reference currents can be given as,

$$i_a^*=I^*,\ i_b^*=-I^*,\ i_c^*=0 \quad (3)$$

Correspondingly, the reference currents through other periods can be generated, which follows the trapezoidal voltage of respective phases. These reference currents are associated with sensed phase currents to generate the current errors as,

$$\Delta I_a = (i_a^* - i_a),\ \ \Delta I_b = (i_b^* - i_b),\ \Delta I_c = (i_c^* - i_c) \quad (4)$$

Current controller

The current controller produces the switching sequence for the voltage source inverter, after associating the current error of each phase with carrier waveform of the fixed frequency. The current errors ΔI_a, ΔI_b, ΔI_c, can remain amplified by gain k1earlier associating with carrier waveform *g (t)*. The switching categorization is generated based on the logic assumed for phase ‘a’ as

Condition-1 k1 $\Delta i_a > g(t)$ then $T_a = 1$

Condition-2 k1 $\Delta i_a \leq g(t)$ then $T_a = 0$

Simulation analysis using single phase DBR control strategy

We have conducted the first simulation analysis using single phase DBR. The simulation has been done following the parameters of BLDC motor drive as suggested by Singh and Singh, (2010) (Table.4)

Power Rating (P)	1500 Watt
Voltage Rating	400V
Current Rating	4 Amp
Stator Resistance (R)	11.9 Ω
Self-Inductance of Stator winding (L)	0.00207 H
Mutual Inductance of Stator winding (M)	-0.00069 H
Peak Voltage of BLDC Machine	32.3
Peak RMS Voltage of BLDC Machine	22.9
Number of Machine Pole (P)	4
Moment of Inertia	7e-006
Mech. Time Constant	0.006

TABLE 4. Design data BLDC Motor

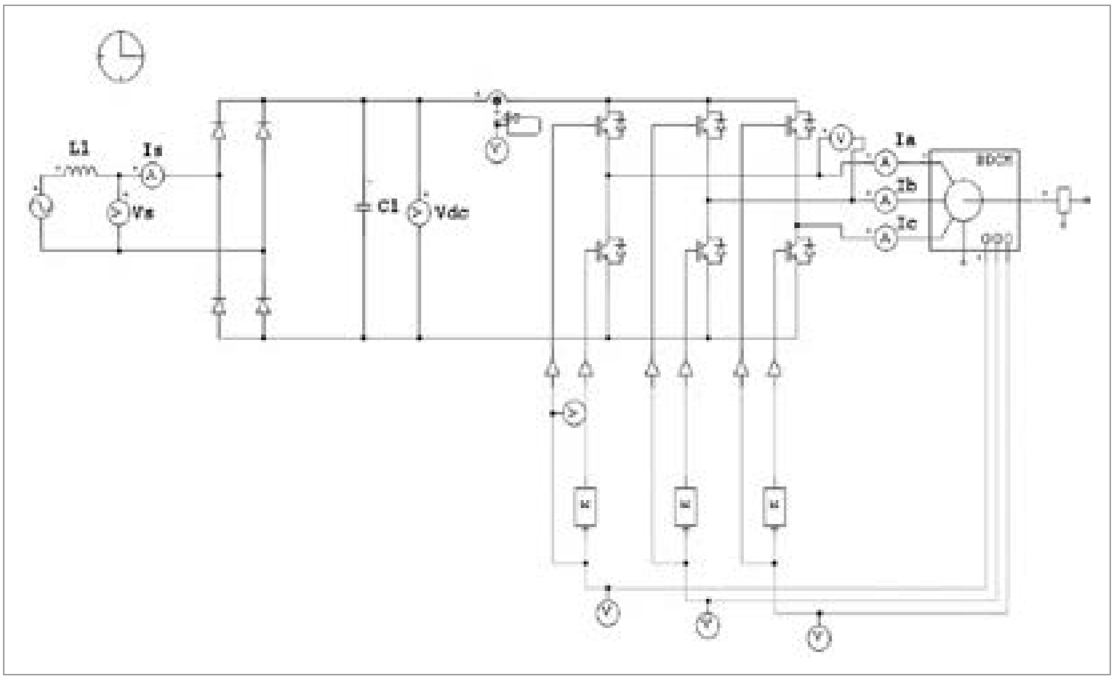

FIGURE 2. PSIM Simulation of BLDC Motor Single Phase Diode Bridge Rectifier fed Voltage Source Inverter

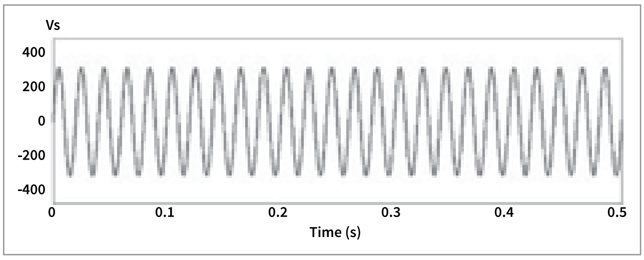

FIGURE 3. Source Voltage of BLDC Motor

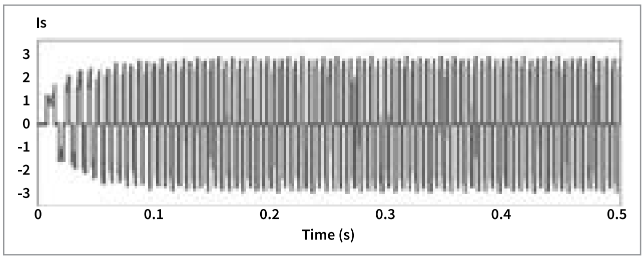

FIGURE 4. Current Waveform of Phase A(Ia)

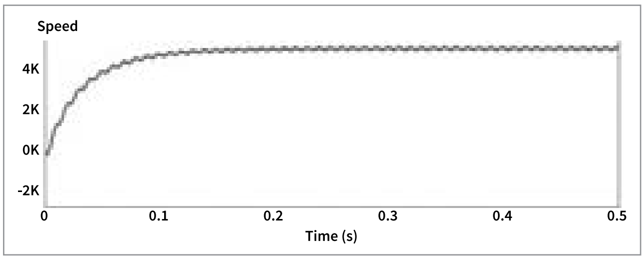

FIGURE 5. Speed waveform of BLDC motor

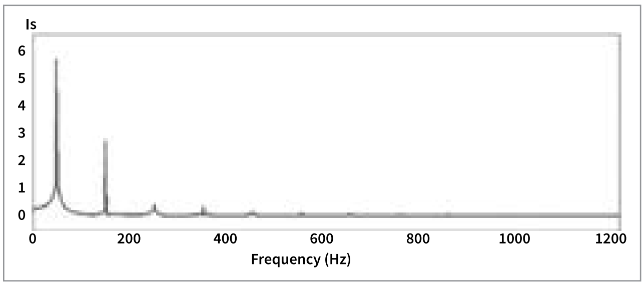

FIGURE 6. FFT Analysis of Supply current (Is)

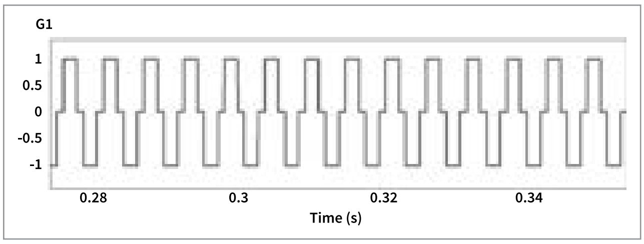

FIGURE 7. Getting pulse g(t)

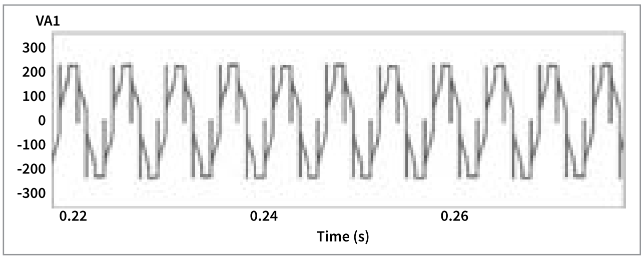

FIGURE 8. Output voltage of BLDC Motor

PSIM Simulation has been done with input source voltage of 230V and input source current of (Is) 3.74 amp. The fundamental frequency selected was 50 Hz. The simulation result shows that the total Harmonic Distortion is 62.53% and Power Factor is 0.84.

Simulation analysis using buck converter control strategy

The second simulation analysis has been conducted using Buck converter control strategy. The simulation has been done following the parameters of Buck Converter as suggested by Singh and Singh, (2010) (Table.5)

Design data of Buck Converter	
Inductor L_o	0.1mH
DC link Capacitor C_o	1500uF
Filter Capacitor C_f	7uF
PI Voltage Controller Gain (K_p, K_i)	0.01, 4.5
PI Speed Controller Gain (K_p, K_i)	0.004, 0.45
Switching Frequency	20 kHz

TABLE 5. Design data of Buck Converter

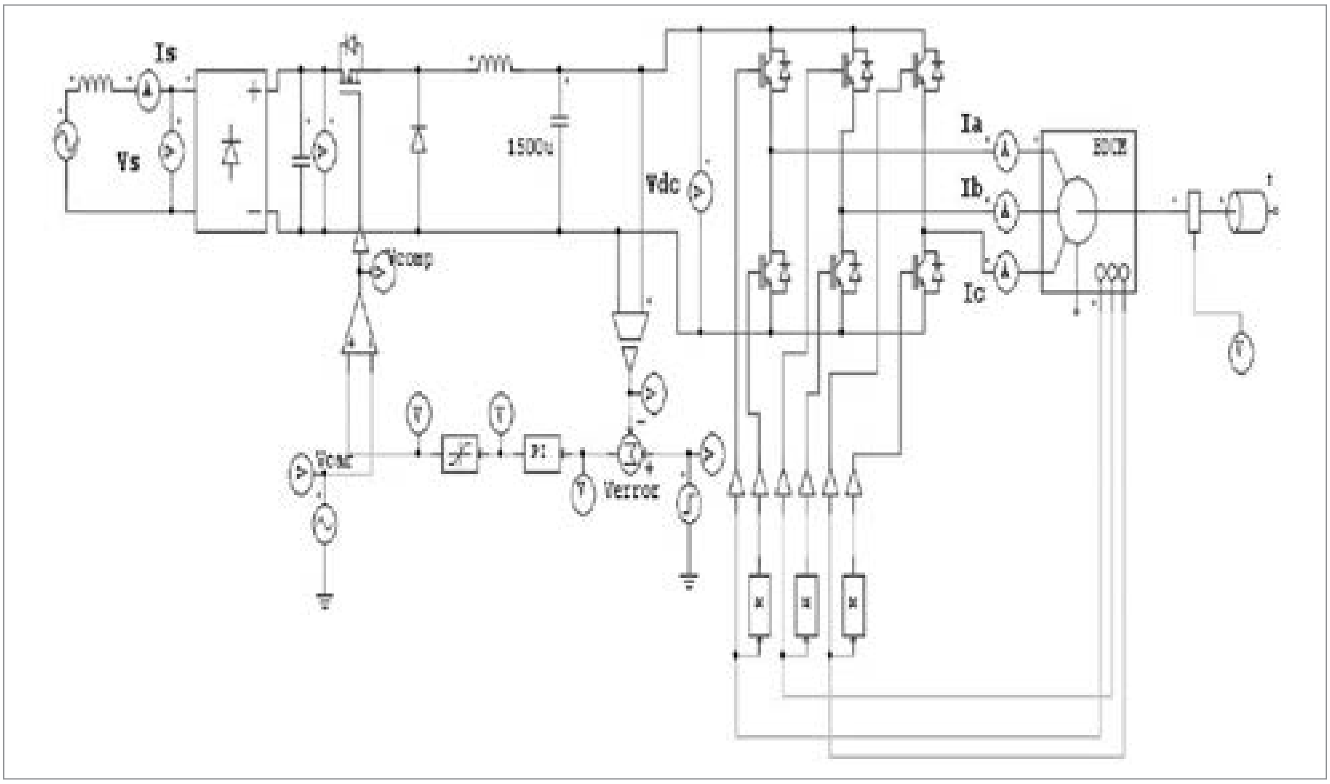

FIGURE 9. PSIM Simulation of BLDC Motor Drive with Buck converters

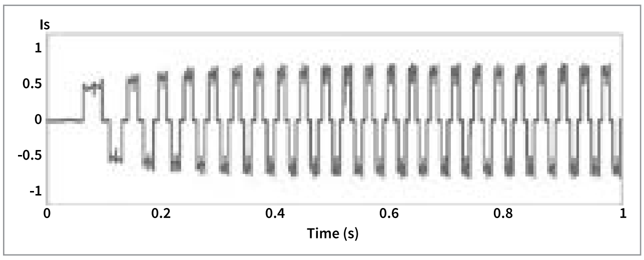

FIGURE 10. Current Waveform of Phase A(Ia)

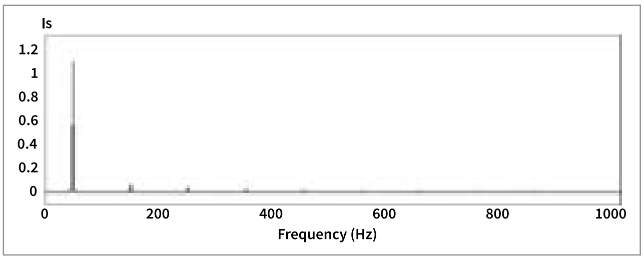

FIGURE 12. FFT Analysis of Source Current

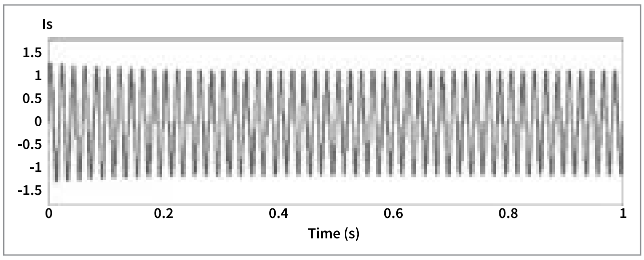

FIGURE 11. Input Source Current

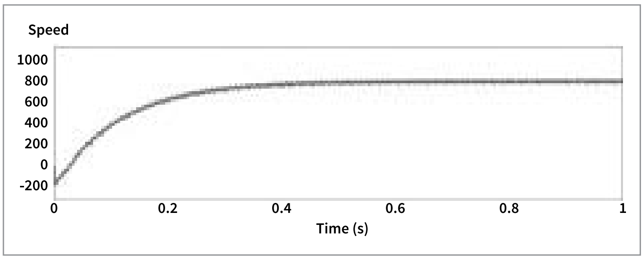

FIGURE 13. Speed Waveform of BLDC Motor

PSIM Simulation has been done with input source voltage of 230V and input source current of (Is) 0.8 amp. The fundamental frequency selected was 50 Hz. The simulation result shows that the total Harmonic Distortion is 8.39% and Power Factor is 0.9963.

Load (%)	THD(I) (%)	PF
10	11.93	0.9924
20	11.58	0.9929
30	11.18	0.9934
40	10.77	0.9939
50	10.37	0.9943
60	9.97	0.9948
70	9.58	0.9952
80	9.18	0.9956
90	8.78	0.9959
100	8.39	0.9963

TABLE 1. Power Quality Parameters at Different Load Condition for Buck Converter fed VSI Based BLDC Motor

Vs	THD(I) (%)	PF
170	7.2	0.9973
180	7.5	0.9970
190	7.7	0.9968
200	8.0	0.9966
210	8.2	0.9964
220	8.3	0.9963
230	8.5	0.9961
240	8.7	0.9960

TABLE 2. Power Quality Parameter with Input AC Voltage Variation for Buck Converter fed VSI based BLDC Motor

Simulation analysis using boost converter control strategy

The third simulation analysis has been conducted using Boost converter control strategy. The simulation has been done following the parameters of Boost converter as suggested by Singh and Singh, (2010) (Table.6)

Design data of Boost Converter	
Inductor L_o	5mH
DC link Capacitor C_o	1500uF
PI Voltage Controller Gain ($K_p$dc, $K_i$dc)	0.05, 1.5
PI Speed Controller Gain (K_p, K_i)	0.01, 0.1
Switching Frequency	20 kHz

TABLE 6. Design data of Boost Converter

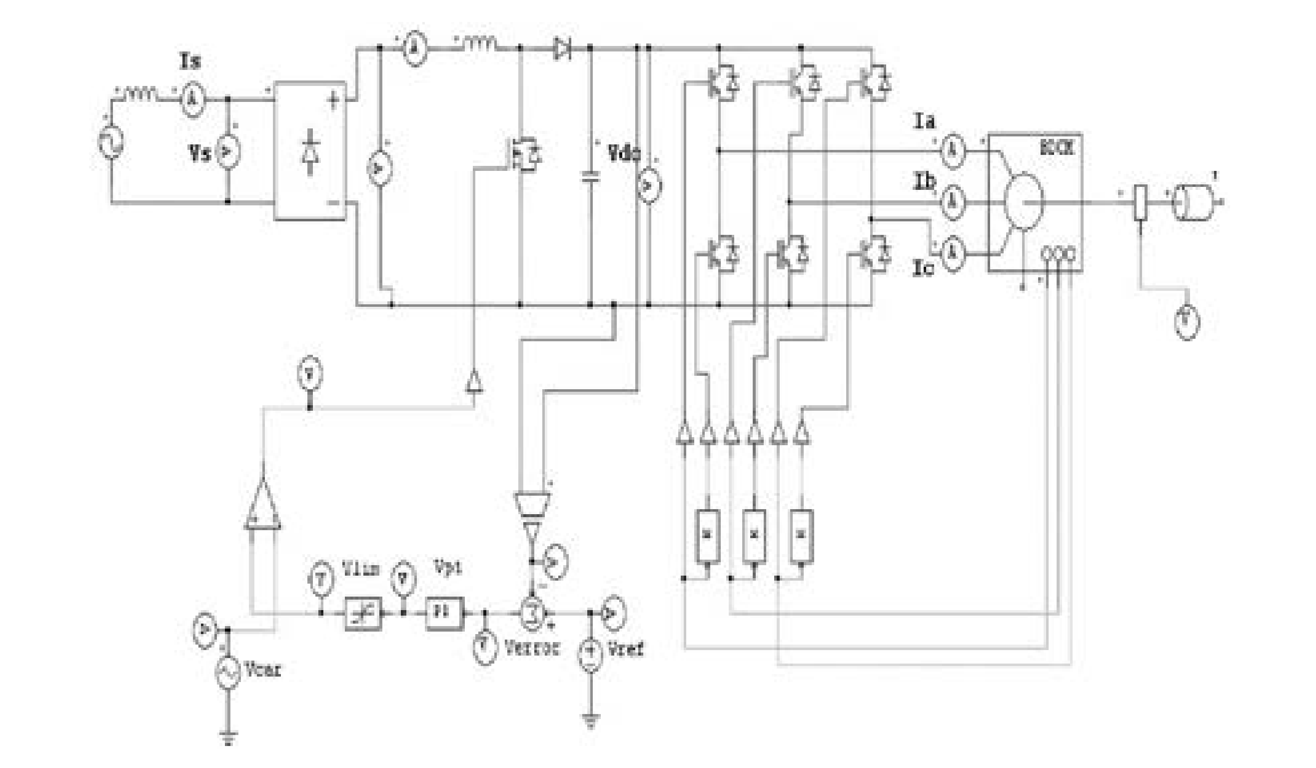

FIGURE 14. PSIM Simulation of BLDC Motor Drive Boost converter

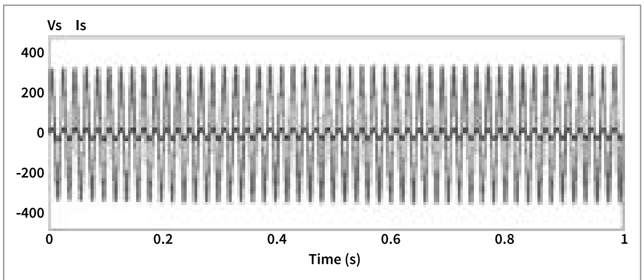

FIGURE 15. Supply current and voltage waveform

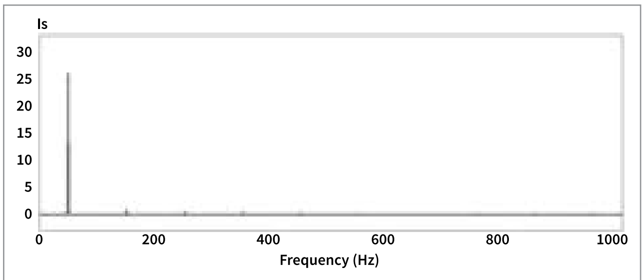

FIGURE 16. FFT Analysis of Source Current

PSIM simulation result demonstrate that using Boost Converter, the total harmonic distortion of source current is decreased to 4.77 % and Power Factor is 0.99.

Load (%)	**THD(I) (%)**	**PF**
10	5.09	0.99
20	5.07	0.99
30	5.01	0.99
40	4.96	0.99
50	4.95	0.99
60	4.90	0.99
70	4.86	0.99
80	4.84	0.99
90	4.81	0.99
100	4.77	0.99

TABLE 3. Power Quality Parameters at Different Load Condition for Boost Converter fed VSI Based BLDC Motor

Vs	THD(I) (%)	PF
170	4.67	0.99
180	4.77	0.99
190	4.81	0.99
200	4.86	0.99
210	4.86	0.99
220	4.87	0.99
230	4.89	0.99
240	4.90	0.99

TABLE 4. Power Quality Parameter with Input AC Voltage Variation for Boost Converter fed VSI based BLDC Motor

Simulation analysis using CUK converter strategy

Finally, simulation analysis has been conducted using CUK converter strategy. The simulation has been done following the parameters of CUK converter as suggested by Singh and Singh, (2010) (Table.7)

Design data of CUK Converter	
Inductor L_1	1.1mH
Inductor L_2	0.5mH
Inductor L_s	0.3mH
Capacitor C_1	0.2μF
Capacitor C_2	1590μF
Switching Frequency	20 kHz
PI Voltage Controller Gain ($K_p dc$, $K_i dc$)	0.05, 4.5

TABLE 6. Design data of CUK Converter

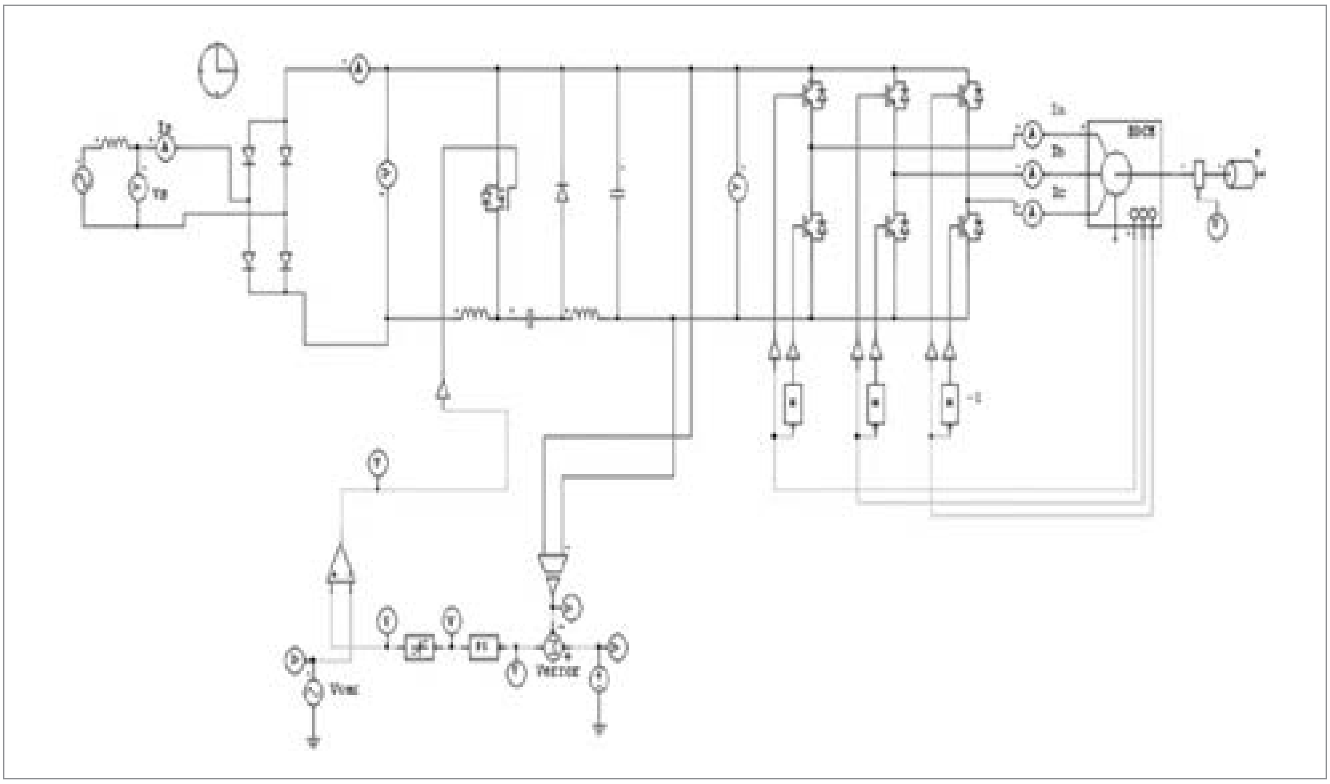

FIGURE 17. PSIM Simulation of BLDC Motor Drive Cuk converters

Bridgeless isolated cuk converter has the following Advantages: (Pireethi & Balamurugan 2016)

(1) It withstands high voltage and vibration.

(2) It withstands high voltage between windings.

(3) It avoid unwanted current loop.

(4) There is an electrical isolation and no electron flow between two circuits.

Load (%)	THD(I) (%)	PF
10	6.11	0.99
20	5.73	0.99
30	5.63	0.99
40	5.63	0.99
50	5.22	0.99
60	4.88	0.99
70	4.55	0.99
80	4.54	0.99
90	4.26	0.99
100	3.98	0.99

TABLE 5. Power Quality Parameters at Different Load Condition for Cuk Converter fed VSI Based BLDC Motor

Vs	THD(I) (%)	PF
170	3.52	0.99
180	3.54	0.99
190	3.67	0.99
200	3.83	0.99
210	3.94	0.99
220	3.98	0.99
230	4.23	0.99
240	4.27	0.99

TABLE 6. : Power Quality Parameters at Different Load Condition for Cuk Converter fed VSI Based BLDC Motor

The PSIM Simulation result demonstrates that Cuk converter fed VSI based BLDC motor is having source voltage (Vs) 230V and source current (Is) 30.47A. The fundamental frequency is 50 Hz. Total harmonic distortion of source current is 3.98% and Power Factor is 0.99.

Conclusion and Scope for Future Work

The paper explained different Power Converter typologies of BLDC using simulation through PSIM software. The speed of the motor has been found proportional to the DC link voltage, therefore a smooth speed control is observed while controlling the DC link voltage. The simulation result shows that total harmonic distortion in AC supply current is reduced and power factor is improved near unity with the help of optimum Cuk converter design as per International power quality standards. Since these motors do not require field winding, they do not have field-circuit copper losses. This increases efficiency, and also because no space is required for field winding, these motor are smaller than corresponding wound-pole motors. The decrease in low-order harmonics and developed displacement power factor is accomplished without the utilized of any voltage or current sensors.

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3

FAULT DETECTION AND DIAGNOSIS METHODS IN POWER GENERATION PLANTS - THE INDIAN POWER GENERATION SECTOR PERSPECTIVE: AN INTRODUCTORY REVIEW

Himanshukumar R. Patel, Dr. Vipul A. Shah

ABSTRACT: The power sector in India is the most significant component of the social overhead capital that effects directly Indian economic through growth of GDP. Since last four decades industrial growth has been increasing significantly, so also power requirements also increasing rapidly. As a result there is low levels of tolerance towards performance degradation in power generation plants (PGPs). Abnormalities or potential faults in power generation plants (PGPs) lead. To situations like low productivity, loss of production, human safety, and environmental hazards. To avoid undesirable conditions and to supply uninterrupted power to industry and other users, power generation industry has started using Fault Detection and Diagnosis (FDD) methods in conventional and renewable energy power generation plants (PGPs) like Nuclear Power Plants (NPPs), Solar Power Plants (SPPs) and Thermal Power Plants (TPPs) to improve reliability and availability of power plants. The paper discusses about different faults related to nuclear power plants (NPPs), thermal power plants (TPPs), and solar power plants(SPPs) and their performance monitoring, instrumentation or sensor calibration, system dynamics, system faults, sensor faults, equipment monitoring, reactor and furnace monitoring, and transient monitoring. The uses of model-based and model-free FDD methods are explained some recent FDD methods are also examined. The popularity of FDD applications is continuously increasing as safety and reliability are significant requirements for different power generation sector. The paper discusses the model-based and model-free FDD methods in NPPs, TPPs, and SPPs types of power generation plants (PGPs).

KEYWORDS

Fault detection, Fault diagnosis, Model-based, Model-free, Nuclear power plant, Thermal power plant, Solar power plant

Introduction

Indian Energy Scenario

India is one of the largest consumers of energy in the world. However, more than 70 percent of its primary energy needs are being met through imports, mainly in the form of crude oil and natural gas. Power generation in the country uses mainly two types of energy sources: conventional and non-conventional energy sources. The use of non-conventional energy sources are increasing since last two decades for power generation because of its inherent advantages of transportation and certainty of availability. However, the conventional energy pollutes the atmosphere to a great extent.

Power generation capacity in India using non-conventional energy (renewable energy) sourcing depicted in Fig. (2) till 30th November, 2017 as per data available in the Ministry of New and Renewable Energy (MNRE) (All India Installed Power Capacity of Power Stations Information, 2017). It must also be noted that India has increased installed power capacity from a more 1362 Megawatts (MW) to over 3,30,860 Megawatts (MW) since independence and electrified more than 500,000 villages. NP electricity consumption in India is expected to rise around 2.28.

Megawatts hour (MWh) by 2021-22 and around 4.50 Megawatts hour (MWh) by 2031-32 (Pankaj Kumar et al., 2016). Therefore complex, instrumentation, and automation are required in the current power generation plant (PGPs) of India for producing more power with higher efficiency and less operating expenses. In that performance degradation. This is where the role of Fault Detection and Diagnosis (FDD) algorithms became very important.

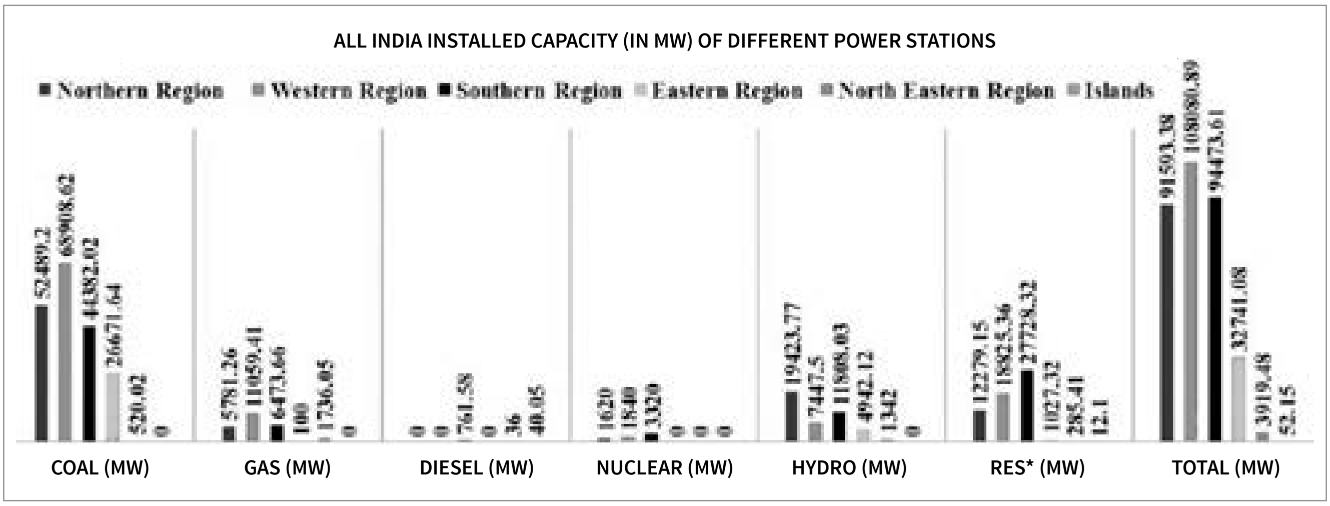

FIGURE 1. Shows total installed power capacity with respect to different regions pertaining to India and conventional and non conventional energy wise (central electricity Authority of India, 2017). All India installed power capacity in (MW) region and type of power generation Wise (Source – The Ministry of New and Renewable Energy (MNRE) as on 30th November, 2017).

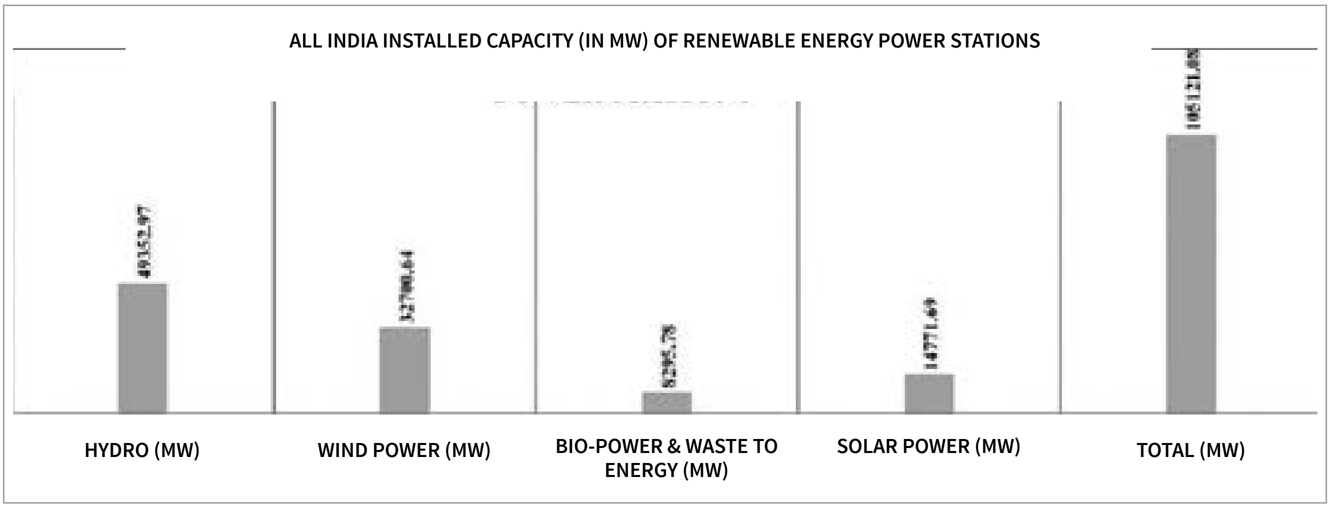

FIGURE 2. All India installed power capacity in (MW) using non-conventional energy. (Source – The Ministry of New and Renewable Energy (MNRE) as on 30th November, 2017).

Model-based methods	**Model-free methods** **Data-driven methods**	**Signal-base methods**
Parity equations Observers	Artificial neural networks (ANN) Multivariate state estimate technique (MSET)	Spectrum analysis Time-frequency analysis (TFA)
Kalman filters Parameter estimation	Principal component analysis (PCA) Partial least squares (PLS) Auto associative kernel regression (AAKR)	Wavelet transform (WT) Autoregressive (AR) signal model Control charts

TABLE 1. Classification of FDD methods.

Fault detection and diagnosis for power generation plants (PGPs)

In a critical system such as PGPs, safety is of major importance. To improve safety, reliability, and capacity factors in PGPs even, preventive actions are desirable. Generally fault is defined as unpermitted deviation or change in characteristics from the desired ones in the system. A failure is a permanent interruption of a system ability to maintain desired performance (Isermann & Balle, 1997). Different faults and failures can occur in instruments, equipment, and systems of PGPs, which can have significant impact on plant performance and productivity. For example, in /(NPPs) can reduce power up to 3% drift in steam generator (SG) (Chan & Ahluwalia, 1992).To enhance efficiency certain PGPs employ heat recovery steam generator (HRSG) to capture energy from the hot combustion gases exhausted from the turbine. Therefore, efficiency of HSRG plays very vital role in improving the efficiency of PGPs. The design in the thermal measurement system for fault detection within a power generation system improves SPPs productivity (Chillar et.al, 2015). Measuring yields by automatic supervision, analyzing the losses, and faults in the present system using automatic fault detection in grid connected PV systems will improve maximum efficiency Power Point Tracking (MPPT) of PV standalone module in diverse climate conditions and will improve power productivity of SPPs,(Silvestre et al., 2013; Joshi Siddharth et al., 2017). Using life cycle and maintenance cost of the wind turbine would be beneficial as this improves efficiency (Walford, 2006; Hastiemian et al., 2006; Hameed et al., 2009). Antonio et al., (2015) proposed that active and reactive power strategies using peak current limiting during the grid faults. Therefore, DG power plants can avoid over current tripping helping to mitigate the adverse effects of grid faults.

Fault detection and diagnosis (FDD) is an advance algorithm to detect, isolate, and identify faults in the system. The first process in fault detection identifies whether a fault occurs in the system. Second fault isolation process implies determination of fault location and, The third most important process identifies the magnitude and time variant behavior of the faults in the system(Isermann and Balle, 1997). The fault diagnosis processes are a combination of two fault detection and fault isolation processes. FDD methods can be applied to monitor a system continuously during operation, which is often referred to as on-line monitoring (OLM). As shown in Table 1. FDD can be classified in abroad spectrum in the model-based methods and model-free methods. Thereafter FDD can be further divided into data-driven methods (multivariable, artificial intelligence based, and signal based methods (single variable, pattern recognition). In model-based methods, a mathematical model is used to represent the ideal or normal behavior of the system. Fault in a system can be detected by checking consistency between predicted output and observed output of the model. The limitation of model-based method is the difference to find out an accurate model that is always hard for every practical system. Data-driven methods rely on correlated measurements of normal/healthy conditions and faulty conditions. Hence the relationship can be formulated by the implicit way by training an empirical model through analysis of fault free training data obtained during normal conditions. The empirical model is used to find out new measurements for faulty conditions, and the fault is detected and fault diagnosis is done by evaluating the residual values statistically. In signal-based methods signal is monitored and exerted (e.g., spectrum) from the measured value with respect to the desired limit. Thereafter FDD decision can be made from the actual signal with standard baseline values. Signal-based and data-driven methods are extensively used for various industries (Chiang et al., 2001; HenryYue & JoeQin, 2001; Venkatasubramanian et al., 2003; Hines and Davis, 2005; Zhang and Dudzic, 2006; Pengand Chu, 2004; Rehorn et al., 2006; Sejdic et al., 2009).

Since the last four decades, various FDD methods are applied in different power generation plants like, NPPs, TPPs, and SPPs etc.(Hashemian & Feltus, 2006;Uhring & Hines, 2005;Ajami & Daneshvar, 2012;Chouder & Silvestre, 2010; Ma, & Jiang, 2011; Jianhong et al., 2015).Especially data-driven and signal-based methods are extensively used in these systems. Applications of FDD methods to solve the problems related to power generation plants (PGPs), presented in Table 2 are briefly summarized in Table 3. These applications lead to safe and efficient plant operations.

Faults	**Examples**	**Impact on an NPP, TPP, and SPP**
	NPPs	
Instrument steady state performance degradation	Sensor drift Sensor bias	Reduced reactor power output Substantial operation and maintenance (O&M) cost, Radiation exposure to personnel
Instrumentation channel dynamic performance degradation Faults in equipment	Pressure measurement slow response due to sensing line blockage Damaged machine bearing Motor winding faults Poor lubrication	Affect system reliability technical specifications not met Reactor trip/scram Plant transients and safety system actuation substantial O&M cost
Loose parts in reactor coolant system (RCS) Plant transients	Detached RCS structures External objects Control rod ejection Loss of normal feed water flow	Potentially affect safety functions and expensive to repair Reactor trip actuation of safety systems
	TPPs	
Steam Turbine Health Monitoring and Control Design fault	Bearing temperature sensor fault Leak fault in lube oil system and turbine shaft axial position proximity switch fault	Reduce efficiency of the steam turbine hence decreasing the overall efficiency of the TPPs.The hazardous situation may occur
Combustion Control Mechanism and Flue Gas Heat Recovery Fault Change in calorific value of the fuel	Actuator or leak faults occur in pipe line which carries the coal and air to the boiler Fuel quality for TPPs	Combustion efficiency reduces and thereafter the insufficient amount of superheated stem to the turbine. Reduce efficiency of the plant
Faults in boiler feedwater control System (Leak) fault	During the load variation actuator fault which carries water in boiler and sensor transients Leakage in pipes containing water, steam or fuel	Affects the boiler safety and efficiency Potentially affect safety functions also trip the turbine system due to the leak of superheated steam
	SPPs	
Constant energy loss Changing energy loss Total blackout Failure in solar PV module	Degradation, soiling, module defect and string defect Shading, grid outage, high losses of low power, power limitation, MPP-tracking, hot inverter and high temperature Defect inverter and defect control devices Yellowing and browning, delamination, bubbles in the solar module, cracks in cells, defects in anti-reflective coating and hot spots caused by the panel acting as a load	Potentially affect safety functions and reduce the efficiency of the plant Permanent failure in control and inverter devices so reduce system reliability Permanent failure in PV module, reduce efficiency and system reliability

TABLE 2. Potential Faults and their impacts on Power Generation Plants (PGPs).

From the view point of NPPs, TPPS, and SPPs, safety and reliability, one the benefits of included in the paper, but are not limited to following:

a. Reduced expose are of radiation to mankind: FDD can lead to improved scheduling of maintenance and repair work for plant and equipments. Therefore, radiation expose are to the nearby mankind can be minimized.

b. Improves instrumentation reliability: Using plant OLM continuously checks the condition of the various plants and equipment. These early warnings or detection of the incipient faults in the plant allows for the corrective action before the critical situation occurs.

c. Avoid actuation of safety/interlocks system: Fault detection is an early stage warming system for detecting a fault in the system. So it prevents any unplanned events (e.g. plant shutdown) in the plant with potentially safety significance.

d. Correct and timely Decision making: On the one part to detect incipient fault detection reduces the chanceof any unwanted situation and helps in diagnosing the fault, and to take corrective action in right time.

e. Improves safety margins: Using different FDD methods monitor and diagnoses the plant operations and helps to avoid uncertainties (e.g, in NPPs core monitor, in TPPs furnace monitor and in SPPs monitor PV modules and grid stability).

From the viewpoint of plant economics, benefits of FDD in various power plants, among other things are as follows:

a. Optimize the maintenance schedule: The correct method and time for maintenance are the major limitation for power generation plants (PGPs) (Hines and Seibert, 2006;Eicker et al., 2005). Condition or OLM based maintenance of instruments and equipment can be accepted.

b. Improves plant reliability: FDD can improve plant reliability for various reasons: first, FDD can do early detection and diagnose incipient faults and avoid unexpected breakdown. Second by it helps to schedule correct plant down-time efficiently and manage the maintenance time. And finally, FDD application helps to improve plant performance, by reduction in various system or plant and sensor faults.

c. Escape from converging a minor problem to major problem: FDD is an advance application which can detect and diagnose the faults early before any dangerous situation happens. FDD is prevents faults from developing into the more critical situation.

d. Power production and system life extension: Using better plant performance monitoring and aging management, production of power is increased and plant life is increased through application of FDD.

Applications	**Data-driven methods**	**Signal-base methods**
Instrument calibration monitoring, Sensor faults	Sensor output estimation	--
Instrumentation channel dynamic performance monitoring, System/ Component fault	(e.g., ANN, MSET, PCA AAKR)	Analysis of measurement noises (e.g., power spectral density (PSD), AR model)
Equipment monitoring, Failure in solar PV module	Sensory data estimation (e.g., ANN, MSET)	Analysis of vibration, motor current, and acoustic emission (AE) signals (e.g., PSD, WT, TFA)
Loose part monitoring, Actuator/ Final control element fault	--	Analysis of structural borne acoustic signals (e.g., spectrum analysis, TFA)
Transient identification, Changing energy loss (Abrupt fault)	Pattern recognition (e.g., ANN)	--

TABLE 3. Applications of Model-free FDD methods in PGPs.

With progress in FDD theory, and its applications on power generation plants (PGPs), and developments in instrumentation and control (I&C) technologies, there is increasing interest in power plant industry to apply FDD. To meet the requirements of safety and economy in power I&C systems more plant data needs to be available for the analysis using advanced FDD methods. Real-time and historical plant data can be analyzed for N performance monitoring of the plants, so as to avoid the critical situations. The power generation industry has also started using wireless communications, which makes cost-effective OLM increasing by feasible (Hashemian,2011;Hashemian et al., 2011b;Kadri et al., 2009).

This paper, reviews model and model-free FDD methods and their applications in NPPs, TPPs, and SPPs. One of the objectives of this paper is to review FDD method and applications on various power plants. Due to the focus of this paper, on model and model-free FDD methods, technical details were kept in the references. The rest of the paper is organized as follows: section 2 presents an introduction to FDD methods on the basis of a survey in terms of model-based, data driven, and signal based methods. Principles of three FDD methods are explained and characteristics of number of a popular techniques are summarized in Table 3 gives an overview of the different applications and Table 5 summarizes data-driven FDD methods and applications related to power generation plants (PGPs), Section 3 includes applications of FDD in TPPs with possible faults summarized in Table 7.Also addressed are some popular techniques for the various faults in TPPs. Section 4 gives a brief summary and subsequently detailed dismission is conducted.

Review Of FDD Methods

Model-based FDD methods

Analytical redundancy is key concepts for most of the modelbased FDD methods. (Willsky, 1976;Chow and Willsky, 1984) In model-based FDD methods normal behavior of the system is represented by a mathematical model of the physical system. Sensor measurements are estimated analytically by other correlated measurements using the model that describes their relationship. The difference between analytical estimated value and actual measured values are labeled as residuals. Any non-zero values of the residuals identify the faults in the system. By analyzing the residual values statistically, faults can be determined (Gertler, 1988;Isermann, 2006). Fault diagnosis methods vary by model structure. However some popular methods improved residuals (Gertler & Singer, 1990;Li & Shah, 2002;Li & Jiang, 2004; Gertler, 2015;Beard, 1971; R. N. Clark, 1978; Frank, 1990;Isermann, 1992; Jia & Jiang, 1995;Isermann, 1993). The model-based FDD methods are divided into three following process: residual generation, fault detection, and identification which are based on the residual evaluation and fault diagnoses by residual analysis (Fig. 3).

As shown in Table 4, system models used for the model-based FDD incorporate both the state space and input-output models. Distinguishing characteristics of the model-based FDD methods are summarized in Table 5. The model-based FDD methods are capable and designed to detect multiple faults and diagnoses simultaneously (Clark, 1978). However, an accurate model is required for the physical system, which can be difficult to obtain for complex systems. The challenging is that, all the faults not considered at the modeling stage may not be detected at all. Further, robustness required against model uncertainty and disturbances (Chow & Willsky, 1984; Lou et al., 1986; Frank & Ding, 1997; Patton & Chen, 1997). To summarize model-based FDD methods are still inadequate at present.

States space model	Input-output model
$X(t) = Ax(t) + Bu(t)$ $Y(t) = Cx(t) + Du(t)$ Where, t is time, X is state vector, A,B,C, and D are system matrix, input matrix, output matrix and D direct transmission matrix with proper dimensions. D matrix is zero in the normal case.	$Y(t) = \varphi^T(t)\theta$ Where, θ consists of model parameters and φ^T (t) contains system past inputs and outputs (Isermann, 1993).

TABLE 4. System models for model-based FDD methods.

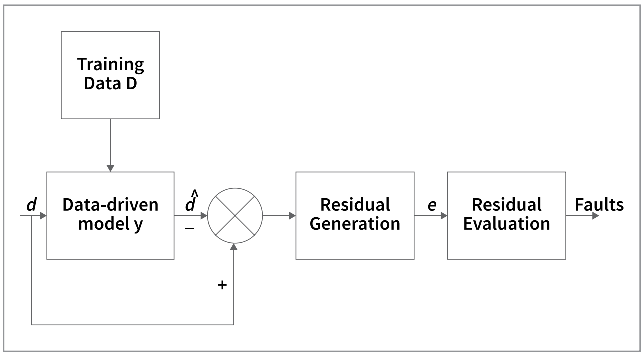

FIGURE 4. Schematic diagram of data-driven FDD methods

Methods	Equations	Comments
Parameter estimation	$\theta = [\varphi^T \varphi]^{-1} \varphi^T Y$ Where, θ is estimation of system parameterθ and φ is a matrix consists of φ^T (t)	Advantage in multiplicative faults[a] Physical coefficients may be recovered for fault diagnosis On-line computation increases costs.
Diagnostic observer	$X\hat{}(t+1) = Ax\hat{}(t) + Bu(t) + K(y(t) - Cx\hat{}(t))$ $e(t) = y(t) - Cx\hat{}(t)$ Where, X is an estimate of X, K is observer feedback gain matrix	Advantages for additive faults for estimation purpose
Kalman filter	$X\hat{}(t+1) = Ax\hat{}(t) + Bu(t)$ $X\hat{}(t+1) = x\hat{}(t-1) + K'(t)e(t)$ $e = y(t) - Cx^{t-1}$ Where, K' (t) is kalman gain	Advantages for additive faults for a system with stochastic disturbances
Parity equations	$e(t) = G(z)u(t) - H(z)y(t)$ Where, e(t) is residue	Advantages for additive faults[b]

TABLE 5. Model-based FDD methods and their characteristics.

[a]An multiplicative faults such as final control element chock up, surface contamination or sludge accumulating on the tank bottom side reflects the change in plant parameters, hence residue leads to depending on system variable.

[b]An additive faults such as sensor bias and system leak faults which leads to a residue that is not depending on system variable.

Various data-driven methods have been developed such as Artificial neural network (ANN) (Anderson, 1995; Watanabe et al., 1989;Venkatasubramanian et al., 1990), principal component analysis (PCA) (Wise and Gallagher, 1996; Dunia et al., 1996; Kaistha and Upadhyaya, 2001), Multivariate state estimation technique (MSET) (Bockhorst et al., 1998; Nela Zavaljevski and Gross, 2000), Partial least squares (PLS) (MacGergor and Kourti, 1995) (Wise and Gallagher, 1996), auto associative kernel regression (AAKR) (Garvey and Hines, 2006), Independent component analysis (ICA) (Hyvarinen, 1999) and Cross-calibration and their modifications (Kramer, 1991; Qin & McAvoy, 1992; Dong & McAvoy, 1996; Scholkopf et al.,1998; Ji-Hoon et al., 2005). Those methods have been extensively applied in various industries.

In various power plants (e.g., NPPs, TPPs, and SPPs), data-driven methods have been studied for different applications like instrumentation calibration, equipment monitoring, reactor core monitoring, transient identification, and furnace monitoring. Amongst the data-driven methods, PCA is the most appropriate and used method due to the fact that is simple and adjustable. There are two methods widely used for applications in NPPs: MSET and ANN, particularly the auto associative neural network (AANN) (Kramer, 1991; Hines et al., 1998). A technique- based on MSET and ANN is used for the smart signal system (Hines and Davis, 2005; Smart Signal, 2010) and process evaluation and analysis by neural operators (PEANO) system (Fantoni et al., 2003) (Fantoni, 2005) developed for OLM in NPPs. ANN has also been studied in power generation plants (PGPs) for transients identification (Bartlett & Uhrig, 1992) (Embrechts & Benedek, 2004), and to estimate important parameters for reactor core monitoring (Dubey et al., 1998) (Souza & Moreira, 2006). Features of PCA, MSET, and ANN methods are categorized in Table 6. Recently, kernel-based machine learning techniques (Cristianini, & Shawe-Taylor, 2004) have been used for pattern-recognition (Vapnik, 1995; Burges, 1998) and fault detection (Lee et al., 2004; Widodo & Yang, 2007; Mahadevan & Shah, 2009; Ma & Jiang, 2010) in various industries. Their applications in different power generation plants have not yet been fully explored.

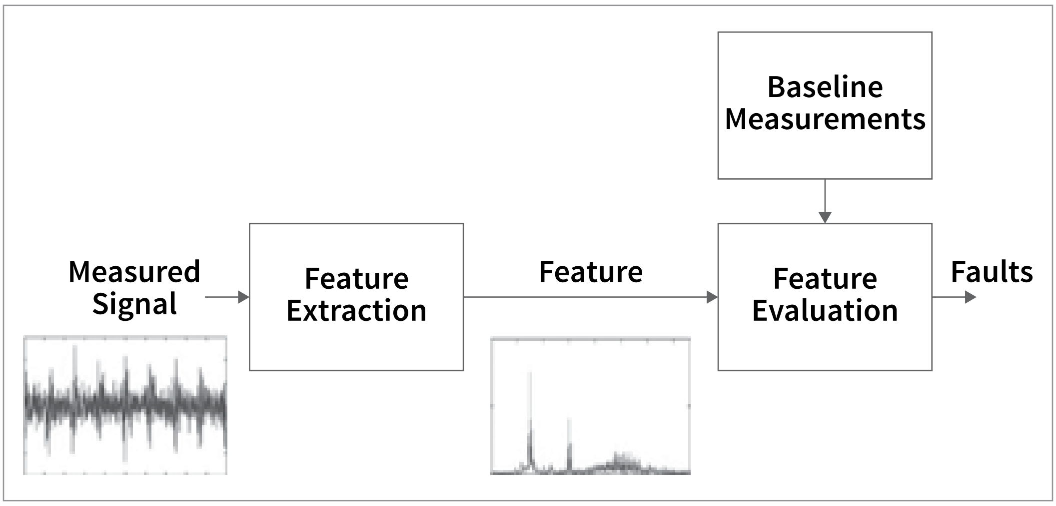

FIGURE 5. Schematic diagram of signal-based FDD methods.

Signal-based FDD methods work by comparing two signals; one is feature extraction from measured signal and the second one for base line characteristics that are considered to be normal operation. Features in terms of frequency domain and time domain have been used, (Fig. 5). Signal-based methods do not rely on the analytical relationship between measured variables. Spectrum analysis is the most used method in signal-based FDD. The spectrum of the measured signal can be obtained using Fast Fourier Transform (FFT). Spectrum analysis is used for NPP instrumentation, equipment, and processes. Time-frequency Analysis (TFA) (Cohen, 1989 ; Hlawatsch & Boudreaux-Bartels, 1992 ; Stockwell et al., 1996) and Wavelet Transform (WT) (Qian, 2002) are extensions of spectrum analysis.

Methods	**Equations**	**Characteristics**	**Power generation plants (PGPs) applications**
PCA	$\hat{d} = \sum_{i=1}^{n} m q_i q_i^T$ Where, q_i is the eigenvector of the correlation matrix of D corresponding to i^{th} largest value and n is the retained principle components.	Simple in use and flexible Linear TPP, SPP	Instrument and equipment monitoring
MSET	$\hat{d} = D \cdot (D^T \odot D)^{-1} (D^T \odot d)$ Where, $\odot$ is a nonlinear kernel operator and D is correlation matrix.	Nonlinear Popular for specially NPP	Instrument and equipment monitoring
ANN	$\hat{d} = F\left(\sum_{i} w_i h_i(d)\right)$ Where, F is a function for, w_i are weights, h_i are other function which calculate outputs using weights, subject to function F.	Nonlinear Popular for specially NPP Popular for pattern recognition Black-box model	Instrument and equipment monitoring, transient identification reactor and furnace monitoring

TABLE 6. Data-driven FDD methods: Characteristics and Application to (PGPs).

Process information using tools such as if-then rules are also used in FDD methods. These qualitative methods can process incomplete information to make FDD decision. Two popular techniques are fuzzy logic and expert systems. Fuzzy logic (Zhang and Morris, 1994), Expert systems (Nelson, 1982;Bernard & Washio, 1989), Genetic algorithms (Holland, 1992), and ANN are the most used techniques in the computational system. Application of the computational intelligence methods in various power generation plants include sensor validation, equipment monitoring, and core or furnace surveillance. Such applications are reviewed in Uhring & Tsoukalas, 1999. Some recent studies and reviews (Na et al., 2001 ; Maeseguerra et al., 2003 ; Gueli, & Mongiovi, 2006 ; Embrechts & Benedek, 2004 ; Zio & Baraldi, 2005 ; Souza & Moreira, 2006 ; Razavi-Far et al., 2009 ; Zaferanlouei et al., 2010). Other qualitative methods studied in the literature include qualitative reasoning (De Kleer & Brown, 1984 ; Weld & De Kleer, 1990; Kuipers, 1994 ; Iwasaki, 1997), signed directed graph (Iri et al., 1979 ; Umeda et al., 1980 ; Kramer & Palowitch, 1987), and case-based reasoning (Aamodt & Plaza, 1994 ; Watson & Marir, 1994). However applications of such methods in NPPs, TPPs, and SPPs are relatively limited at present.

Applications of FDD methods in TPPs

In the thermal power plants (TPPs) it is a fact, that maintenance cost of the TPPs is goes up to 30% of the total production cost of the electricity (Ulrich,2004). According to the script by U.S Department of Energy (DOE) The costs of Combined Heat and Power Installation Database (Technology characterization – steam turbine by US EPA, 2015), for a typical steam turbine the may fall by 0.004 $/kWh-year. For the study combined cycle power plant, it is reported that the maintenance cost may to amount to 17% of the plant life cycle cost (Boyce, 2006). In fig. 9 percentage wise costs are given during the plant life cycle for a combined cycle power plant.

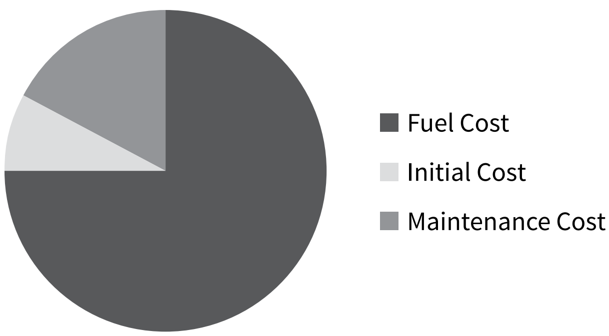

FIGURE 9. Plant life cycle cost for a combined cycle power plant (Jerome, R, 1989).

From the various heads for the plant life cycle cost, the main and controllable head is maintenance cost. In the light of data, it can be said that any improvement in the performance of the existing maintenance practice leads to significant cost savings. This reflects into less production cost of the electricity and economic benefits for the customers. Indeed, a study by Rosen (Jerome, R, 1989) has revealed that a saving of about 30% in maintenance cost can be achieved by simply changing from preventive maintenance to Condition Based Maintenance (CBM) in which a Fault Detection and Diagnosis (FDD) system plays a major role. Advancement into FDD algorithm, therefore, would mean significant improvement in the CBM capacity.

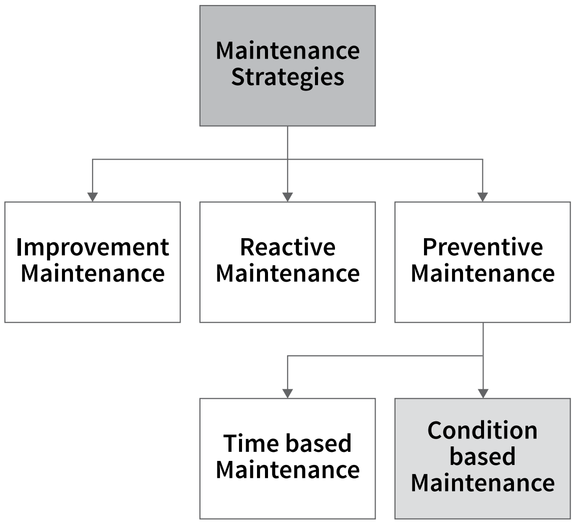

FIGURE 10. Types of Maintenance Strategies.

There are three types of maintenance strategy, (Fig. 10). The first one is Improvement Maintenance (IM) that deals with maintenance considerations at the manufacturing stage of the equipment itself. The intention of this strategy is to do away with any maintenance requirement, due to the limitation of the material properties and manufacturing method, and design the parts and equipment for finite life. It is however, difficult to implement this strategy practically. The second one is called Corrective or Reactive Maintenance (CM). In this kind of approach parts are replaced when they fail (It is adoptable when the frequency of the failure of parts is high. It however causes unnecessary down-time leading to production losses. The third type is known as Preventive Maintenance (PM).Further PM is divided into Time-Based Preventive Maintenance (TBM) and Condition Based Maintenance (CBM). TBM schedule is predefined and applied to the plant or equipment to prevent failure before it occurs. Unlike TBM, CBM is a proactive strategy in the sense that it is recommended based on existing conditions of the plant. The advantage of the CBM strategy is that it reducing unnecessary shut-down and maintenance costs.

For improving efficiency of the TPPs and reducing the production costs CBM strategy is employed in TPPs. CBM involves three steps: data acquisition, data processing, and decision making (Jerome, 1989). For the successful application and execution of the CBM scheme state-of-the-art scheme is used like FDD.

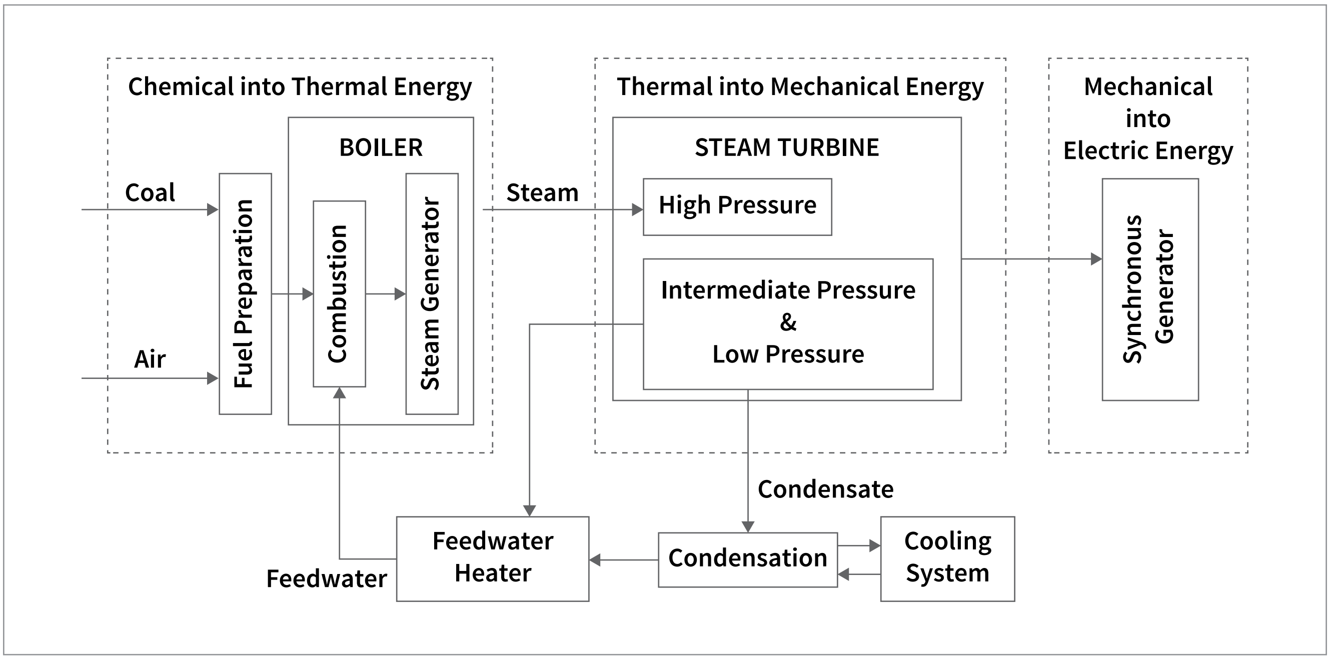

FIGURE 11. Energy Cycle in TPPs.

Thermal Power Plant (TPP) in Brief

Thermal Power Plants (TPPs) deliver electricity that could be either from natural gas or coal. The typical three forms of energy conversation in different steps of TPPs is illustrated in Fig. 11. To convert chemical energy into electrical energy in any TPPs, several closed loop controls are used. To improve the overall efficiency of the plant,all the closed loops should be closely monitored and precisely controlled. In every closed loop system in the plant there are three type of fault. The first being system fault in which the mechanical structure of the system or component is prone to damage (i.e. leak fault in pipe lines or in the tank). The second one is actuator fault in which the characteristic of the actuator changes due to mechanical wear and tear(i.e. in pneumatic actuator faults incorrect pressure supply, diaphragm leakage, plug aging etc.)This may drastically change the system behavior, resulting in degradation or even instability. The third fault is sensor fault in which measured value may be high or low from the actual one (i.e. sensor accuracy, miss calibration etc.). All three types of fault in any closed loop system represents in fig. 12. By applying FDD methods into closed loop system incorporating effective maintenance schedule, gives optimum efficiency of the overall plant. Improving efficiency and reliability of the TPPs depend upon the steam turbine controls.

Detailed working flow diagram and possible faults and failures in TPPs are demonstrated for TPPs in fig. 15.

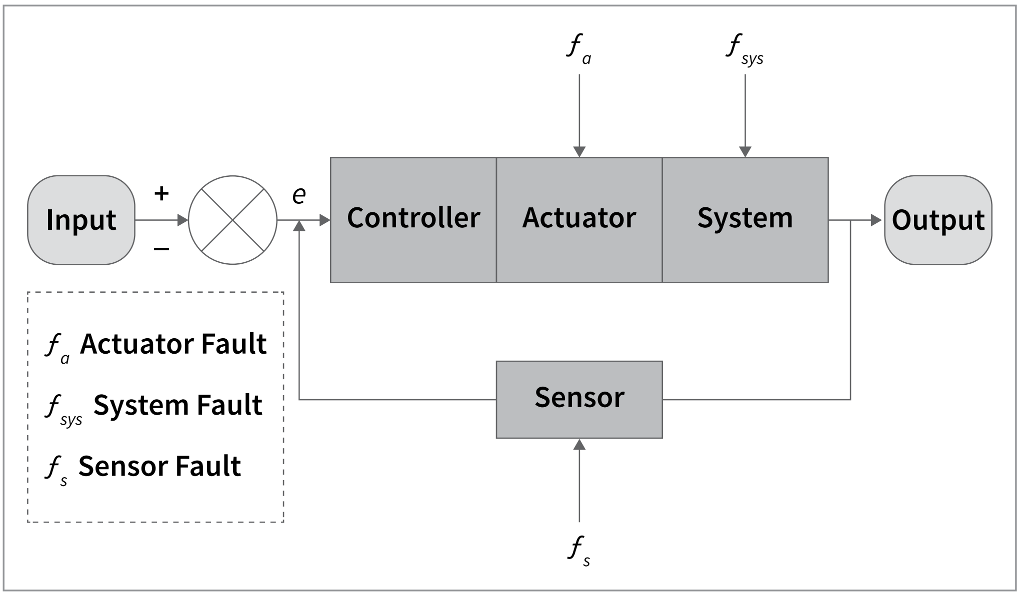

FIGURE 12. Potential faults in any closed loop system.

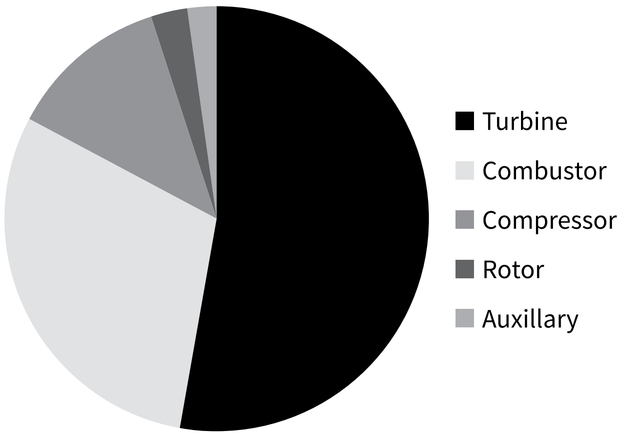

FIGURE 13. Major failure in a steam turbine for low capacity less than 220 MW TPPs. (Jerome, R, 1989).

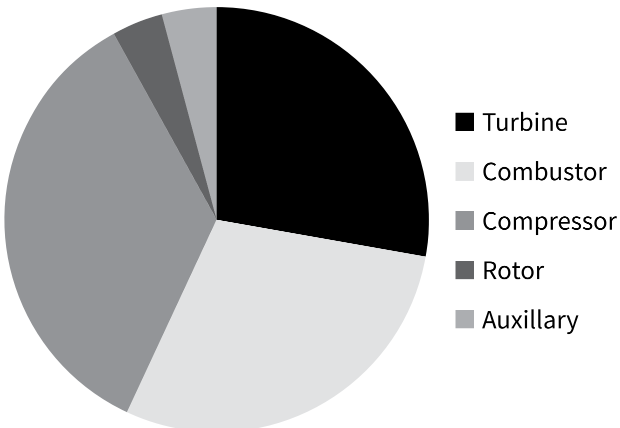

FIGURE 14. Major failure in a steam turbine for high capacity more than 220 MW TPPs (Jerome, R, 1989).

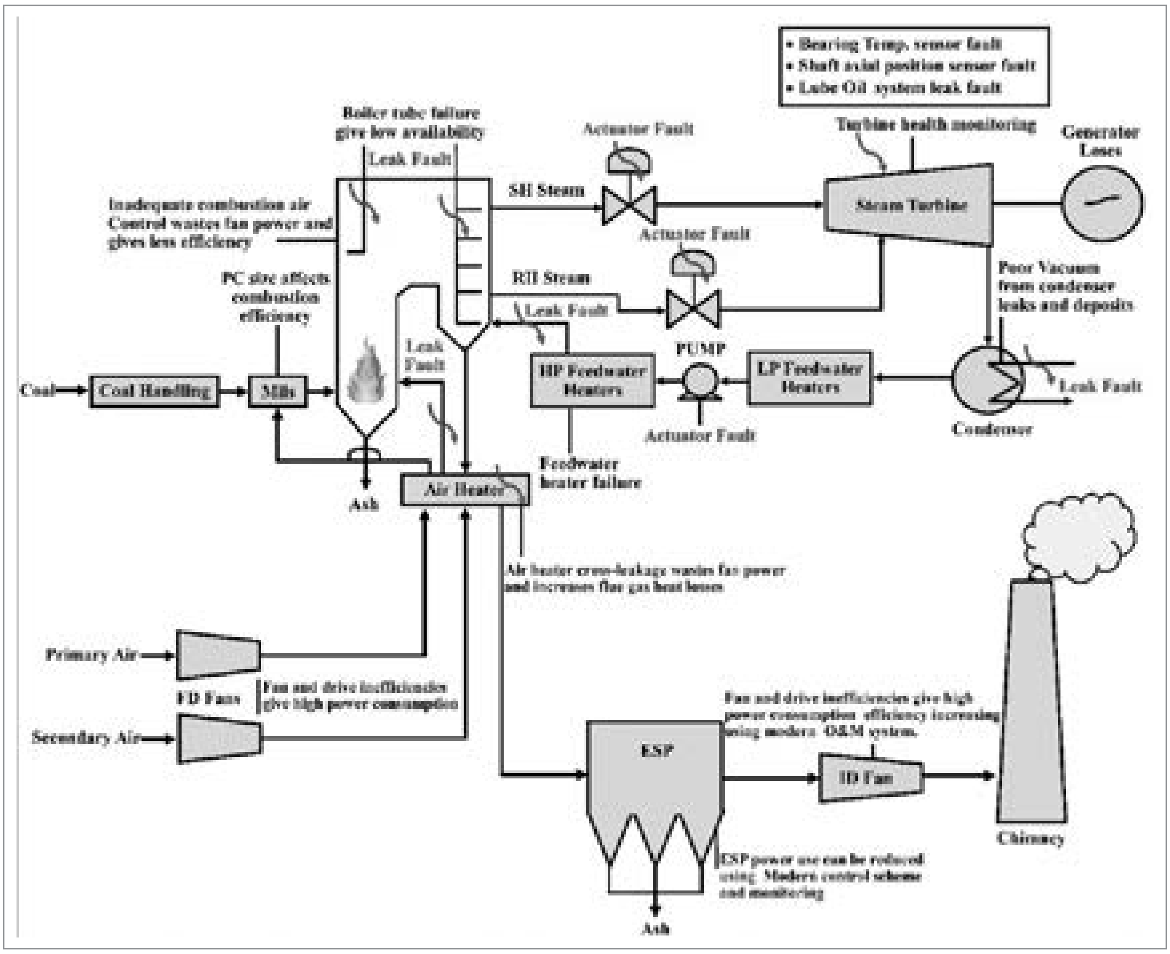

FIGURE 15. TPPs working flow with possible failure and faults.

Possible Faults in TPPs	**Description**	**Remarks**
Steam Turbine Health Monitoring and Control Design	Indeed, turbine health monitoring and control is an essential part in the thermal power plants (TPPs) to improving efficiency. However fault occurs (i.e. sensor, actuator and system faults) during the operation of the turbine. Increasing steam turbine efficiency and output, various FTC strategies have been applied.	The steam turbine in TPPs may cause major losses in terms of efficiency and maintenance. It is major equipment in any TPPs. Maintenance cost leads to significant change in the efficiency of TPPs.
Combustion Control Mechanism and Flue Gas Heat Recovery	Combustion controls adjust coal and air flow to optimize steam production for the steam turbine/ generator set. In TPPs, steam reheater or super heater pipe leakage may reduce combustion efficiency, steam temperature, furnace slagging and fouling, and NOX formation.	For proper combustion control in boiler,continuously provide sufficient amount of air and fuel, System fault occurs in stem heater, super heater and reheater and fuel pipe line, dropping the combustion efficiency. Heat recovery is important for utilizing maximum energy from the flue gases. Leaks faults leads to in heat recovery cycle occurs energy losses.

Possible Faults in TPPs	Description	Remarks
Boiler Feedwater Control	The drum water level control is essential in boiler control. Due to increasing and reducing demand of the steam drum water level must be controlled precise, by Actuator faults, lead to the hazardous situations which may be due to an insufficient amount of water in the boiler drum.	Actuator fault occurs in the power plant system reduce efficiency of turbine due to an insufficient amount of superheated steam produced by the boiler.

TABLE 7. Possibly Potential faults in TPPs with a brief description.

Heat Recovery steam Generator (HSRG) is a part of TPPs. The HSRG has a steam drum, water drum, water-walls, economizer, pre-heater, and feed-water pumps as sub units. The prominent performance related faults common in the units include malfunction in the feed-water pump (actuator) (i.e. damaged seals and erosion of impellers), tube leaks (system fault), and fouling in the remaining critical components. Fouling in the HSRG causes the exhaust gas exit temperature to increase, and exhaust gad pressure and steam production to decrease (Port & Herro (1991). Possible faults in TPPs are summarized with a brief description in table 7. The steam turbine fault is a major fault in TPPs from the perspective of economic

losses due to failure or lack of maintenance of the steam turbine. Maintenance expenses in the TPPs is fora steam turbine. So,detecting an early fault in turbine and diagnosis is mandatory for reliability of the power plant. Several researchers have focused on various FDD methods that are applied to the turbine for TPPs(Dhinietl., 2017; Karlsson, 2008 ; Bin, 2012 ; Changfeng, 2009 ; Zwebek & Pilidis, 2003). The other major faults are small function insensor in the TPPs. The sensor is an essential part of any closed loop system for measured variable, and a malfunction in sensor results in deviate the controlled variable significantly, and hence affects the plant efficiency. The various FDD methods are applied to prevent sensor faults (Toffolo, 2009; Kusiak, & Song, 2009) (Mehranbod, 2005;Mehranbod & Soroush, 2003; Cho, 2004). The third important fault is actuator fault.Plays.Failure to control variable would degrade the quality and further to dangerous situations. If the actuator fails or of a fault occurs,in boiler drum water level control, the superheated steam quantity reduces drastically and affects the efficiency of the turbine Low levels of water in tubes damage due to overheating by the superheated steam. If combustion control fail affects the combustion efficiency. To overcome the effect of the actuator fault in a system various FDD methods discussed are(Dhini, 2017; Bin, 2012;Changfen, 2009; Karlsson et al., 2008; Karlsson et al., 2008; ZwebekPilidis, 2003).

Summary and Discussion

In this paper, an overview of FDD methods is presented in the field of different power generation plants (PGPs). Vibration monitoring and loose part monitoring, noise analysis have beenextensively applied with success in various PGPs. It is recognized that on-line monitoring of instruments andequipment in power plant industry brings benefits to plant availability and results in better economy. Some commercial products have been developed and are increasingly used in power plants. Encouraging results have been obtained for reactor core monitoring in NPPs, furnace temperature monitoring in TPPs, and transient identification. Application of FDD in NPPs, TPPs, and SPPs (PGPs) will become more beneficial as I&C technologies and FDD methods theory progress. Application of model-based FDD methods are very because of complex plants like NPPs. Signal-based FDD methods have been proven useful for instrumentation channel dynamics performance monitoring, and equipment vibration monitoring. Transient identification is basically a pattern recognition problem, with ANN dominating in this area. Emerging pattern recognition methods have not yet been explored. For the TPPs various faults are considered and appropriateFDD methods are discussed.

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4

A FRAMEWORK FOR DEVELOPMENT OF RISK SEVERITY THROUGH THE APPLICATION OF FUZZY EXPECTED VALUE METHOD (FEVM) FOR INFRASTRUCTURE TRANSPORTATION PROJECT

Manvinder Singh, Debasis Sarkar

ABSTRACT: Mega infrastructure transportation projects are exposed to very high uncertainties and critical risks due to complexity starting from pre-conception to operation phase of a project life cycle. Hence, fully organized method of risk assessment is required for the formulation of risk detection and mitigation measures. This research work is an effort to determine risk severity and risk ranking of the various risky activities of elevated corridor metro rail projects using Fuzzy Expected Value Method (FEVM). Fuzzy logic is incorporated within conventional Expected Value Method (EVM) to map the interrelationship between probability of occurrence and impact generated for a particular activity. Based upon fuzzy risk severity values, it has been concluded that erection of pre-cast segments, detailed project report and feasibility, land handing over, traffic diversion and piling activities are having very high fuzzy risk severity values and came under first five ranks with respect to risk involved and associated with them. The developed fuzzy risk severity values would enable the project authorities to identify the activities with high risk severity and to take the mitigation measures accordingly.

KEYWORDS

Risk severity, Fuzzy expected value method (FEVM), Elevated corridor, Metro rail project, Infrastructure transportation

Introduction

Rapid economic development has augmented the demand for the construction of public and private infrastructure and facilities in metropolitan areas worldwide and has resulted in the undertaking of numerous public construction projects which are very uncertain and risky due to complexity and problems in utility diversion, land acquisitions, approval of funds from government authorities and financial institutions, safety and environmental issues. Mostly government authorities and construction firms fail to take a proactive approach regarding risks involved, which results into huge cost overruns and delays. Hence for the successful completion of the project with respect to cost, time, scope, quality and safety, potential risk should be identified, prioritised and accordingly risk mitigation measures have to be implemented.

This research work is an effort to determine risk severity and Fuzzy Expected Value Method (FEVM) ranking of the various major risky activities of metro projects using Fuzzy EVM (FEVM). This FEVM ranking helps the project management team to develop and implement risk mitigation measures to avoid undue time and cost overrun in projects.

Literature Review

Askari, Reza, and Ghane (2014) stated that, effective risk management techniques are required to cope up with various construction activities. Hence identification and assessment of the important risks involved in infrastructure projects is essential. Klose, Damm, and Terhorst (2015) stated that, most common method for transportation related studies is expert interviews, questionnaire surveys and cost surveys. Liang and Wey (2013). expressed that, proper planning of transportation infrastructure projects can have significant impacts on urban development. Kangiri (1995) stated that, significant risks associated in all execution projects are mainly affected by wrong safety practices, improper quality, lack of competence and technical know - how.

Johnsen and Veen (2013) had carried out risk assessment of Norwegian railway using emergency communications and was based upon preliminary hazard analysis. Their work seems to have improved the total system resilience. Park and Papadopoulou (2012) analysed questionnaire data to rank causes of cost overruns according to their frequency, severity and significance. Ameyaw and Chan (2015) had prepared risk factor list, ranking of factors and describes the "top-ranked" risk factors. Their study on Public Private Partnership (PPP) water supply projects would help Governments and investors to develop feasible risk mitigation strategies. Liang and Wey (2013) carried out their work on allocation of resources and the risks and uncertainties associated with the highway development projects. They developed a risk a robust risk management model based on Monte Carlo simulation and Analytic Network Process (ANP). Klose et al. (2015) studied the risks and vulnerabilities due to occurrence of landslides and further made an attempt to develop a cost model which would quantify the approximate damage created by the landslides and also its impact on society.

Sarkar and Dutta (2011) have studied and identified the risks associated with the construction of underground corridor for metro rail operations. They developed a risk management model which classified the risks according to severity and recommended suitable risk mitigation measures. Jannadi and Almishari (2003) worked on a basic risk management model which can assess the different risk and hazard categories of a construction industry. A comprehensive model by using Analytic Hierarchy Process (AHP) and Failure Mode Effect Analysis (FMEA) was developed and validated by Abdelgawad and Fayek (2010). Choi, Cho, and Seo (2004) applied fuzzy concepts for developing user friendly risk analysis software's particularly for underground construction projects. Chan et al. (2009) had thoroughly reviewed the fuzzy literature for last two decades. Li and Zou (2011) had proposed Fuzzy AHP Method for PPP Projects. Bhagat (2017) shared his experience in developing a community based disaster mitigation strategies for natural and man-made disasters. According to him community participation and awareness is the most essential component for achieving sustainability in dealing with disasters. Shah, Mehta, & Mukhopadhyay (2017) studied the financial risks and challenges faced by the investors and consumers of solar PV. The impact on the financial challenges were studied by comparing cash flows, Net Present Value (NPV), Internal Rate of Return (IRR) and pay back periods. Further, Singh et al. (2017) made a comparative study of the risk analysis methods like EVM and Fuzzy EVM for complex infrastructure projects like construction of elevated corridor metro rail constructions. Singh et al. (2017) also applied Modified AHP (MAHP) for computing the risk severity index for elevated corridor metro rail projects.

Methodology and Conceptual Framework

Modified EVM is used for the risk analysis. We have extended the work of Sarkar & Dutta (2011) by incorporating fuzzy in EVM. The variables are defined as below:

P_{st}: Probability of s^{th} risk source for t^{th} activity

W_{st}: Weightage of s^{th} risk source for t^{th} activity

I_{st}: Impact of s^{th} risk source for t^{th} activity

Every activity is having various risk sources, probability and risk impacts. The value of probability and impact of risks should range between 0 to 1. The detailed questionnaire was prepared after brain storming session with experts. The questionnaire consisted of 24 major risk categories and 255 questions and these were distributed to 77 experts out of which 62 experts (80%) answered the questionnaire.

$$\sum_{s=1}^{M} W_{st} = 1 \text{ for all t } (t = 1\ldots N) \quad (1)$$

The Probability(P_{st})for every activity, 't' can be clubbed and represented as a composite Probability factor (CPF_t). W_{st} of the sub-risk activities are multiplied with their respective probabilities to achieve the CPF of the major risk categories.

Composite Probability Factor $(CPF)_t$=

$$\sum_{s=1}^{M} P_{st} . W_{st} \text{ for all t} \quad (2)$$

Composite Impact Factor $(CIF)_t$=

$$\sum_{s=1}^{M} I_{st} . W_{st} \text{ for all t} \quad (3)$$

$$0 \leq I_{st} \leq 1 \sum_{s=1}^{M} W_{st} \text{ for all t}$$

CPF and CIF are to be computed for each risk category from the feedback of every expert.

For the incorporation of fuzzy into EVM, there is a need to define membership function for probability, impact and severity. Triangular fuzzy numbers due to its simplicity were used for defining the membership functions. 25 fuzzy rules were framed on the basis of five risk classifications of probability and impact Sarkar and Dutta (2011). Sarkar and Dutta(2011). The values of the linguistic scale for each membership function are taken from 0 to 1 at an increment of 0.25.

Case Study

The case study considered for this research work was Ahmedabad metro rail project. The total operation of the project is being executed by Special Purpose Vehicle (SPV) M/s. Metro Express-Link Gandhinagar-Ahmedabad (MEGA) a Government of Gujarat undertaking. The length of the corridor is 8.21 kms (Thaltej Gam to West Ramp stretch) part of East-West line (20.73 km). The construction work of this stretch was awarded to M/s. Tata Projects Ltd and China Civil Engineering Construction Corporation. It consists of seven numbers of elevated stations like Stadium Circle, Commerce Six Road, Gujarat University, Gurukul, Doordarshan Kendra, Thaltej and Thaltej Gam. Total number of piles and piers to be executed are 1152 and 278 numbers respectively. For this stretch, 1950 segments are to be casted and erected. The weight of each segment is 48 tons. The total cost of the project is approx. 721 cr.

Case Analysis and Results

The CPF and CIF computed by EVM for all major risky activities which were about twenty four in number were used as inputs for fuzzy EVM method by using Mathworks. Matlab.R2014a version software. The outputs are risk severity values obtained for all twenty-four major risky activities. Table 1 is the representation of CPF and CIF values for four major risks of the Ahmedabad metro project (case study stretch). Figure 1 represents the final Fuzzy risk severity of erection of pre-cast segments.

Serial No.	**Activity Name**	**Composite Probability Factor (CPF)**	**Composite Impact Factor (CIF)**
1	Risks in traffic diversion	0.460	0.790
2	Risk in utility diversion	0.299	0.694
3	Risks in erection of pre-cast segments	0.460	0.790
4	Risks in piling activity	0.263	0.777

TABLE 1. CPF& CIF Values for Four Main Risky Activities of Ahmedabad Metro Project

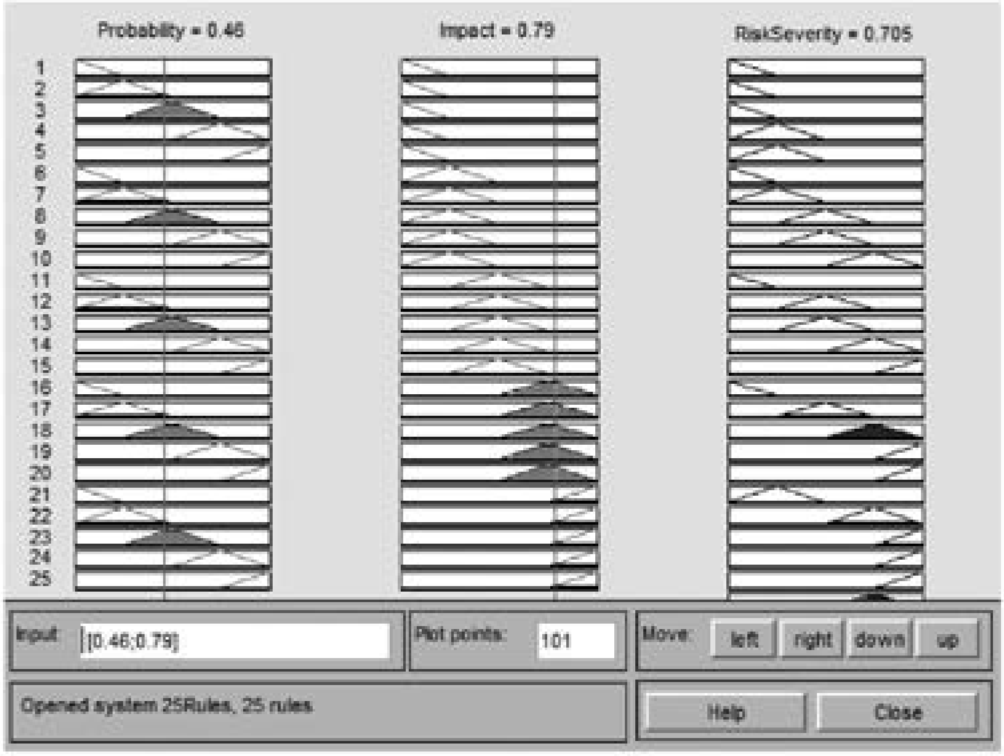

FIGURE 1. Final Fuzzy Risk Severity of Erection of Pre-Cast Segments

The final fuzzy risk severities of five risk categories out of the 24 major risks in the construction of Ahmedabad metro rail project are presented in Table 2.

Serial No.	Activity Name	Quantitative Fuzzy Risk Severity	Qualitative Fuzzy Risk Severity	Fuzzy EVM Ranking
1	Risks in erection of pre-cast segments	0.705	Critical	1
2	Detailed Project Report and Feasibility	0.299	Critical	2
3	Risk in Land handing over	0.643	Very High Risk	3
4	Risks in traffic diversion	0.624	Very High Risk	4
5	Risks in piling activity	0.560	Very High Risk	5

TABLE 2. Fuzzy Risk Severity Values of five Risk Categories

Result Interpretation and Discussion

The fuzzy risk severity values and risk rankings for major risk categories of Ahmedabad metro project as attained from fuzzy EVM were computed. By application of FEVM, risks in erection of pre-cast segments is having highest quantitative fuzzy risk severity value of 0.705 and are considered to be critical in terms of qualitative risk classification. This activity has obtained fuzzy ranking of one. Risks in Detailed Project Report and Feasibility activity are also critical with quantitative fuzzy risk severity value of 0.684 which obtained second rank. Risk in activity land handing over is having very high fuzzy risk severity value both quantitative (0.643) and qualitative and has obtained third rank. Risks in traffic diversion are very high both quantitative (0.624) and qualitative and has obtained fourth rank. Risk in piling activity works are also very high both quantitative (0.560) and qualitative and has obtained fifth rank. Risks in launching girder, obligatory span, risks in pile test, expansion joint, casting of segment, Risks in road widening, barricading, parapet erections, utility and traffic diversion works are categorised and mapped as risks which are critical. Risks in casting yard setup, cable tray, parapet casting and project office set up falls under medium risk severity category.

Conclusion

The analysis carried out from the above research work helps us in identifying and ranking the major activities which has high degree of risks and uncertainties involved and associated with it. Analysis by FEVM method has highlighted that risks in activities like erecting of pre-cast segments, detailed project report and feasibility, land handing over, traffic diversion and piling activities are showing risk severity values of 0.705, 0.684, 0.643, 0.624 and 0.560 respectively which fall under the category of very high risks. The project authorities need to monitor these risks with high degree of carefulness, failing which these activities would lead to time overrun and cost overrun of the project which would finally lead to project failure. One of the limitation of this research is that the values of CPF and CIF are obtained from questionnaire survey which need to be consistent and validated with simulation studies.

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5

DESIGN PARAMETERS OF SHUNT ACTIVE FILTER FOR HARMONICS CURRENT MITIGATION

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ABSTRACT: This paper explains the design parameters of three phase shunt active filter based on PQ theory for mitigation of harmonics current. Design parameters include design of DC link voltage and design of filter inductance. Design parameters have very important role in performance of shunt active filter. If design is appropriate filter can respond to dynamic load condition along with steady state conditions. SAF can mitigate almost all current harmonics efficiently by effectively designing the parameters.

KEYWORDS

SAF, p-q theory, non-linear load, Hysteresis current control

Introduction

In last two decades, Pulse width Modulation(PWM) based power electronic devices have gained popularity for various industrial applications such as adjustable speed drives, renewable energy applications, UPS's, etc. Their vast use is because of many advantages such as controlled DC bus voltage, bi-directional power flow, etc. PWM based devices have certain disadvantages too as they introduce current and voltage harmonics in the power system, resulting in instability, voltage distortion, etc. Shunt active filters have proven to be excellent solution for current harmonics mitigation due to the use of non linear loads in power system.

Examples of harmonics producing load are computers, adjustable speed drives, semiconducting devices, etc. (Singh, Haddad, & Chandra, 1999). mitigation of harmonics can be done with the help of passive filters or active filters. Hybrid of active and passive filters also solves problems of harmonics. While shunt active filters are useful for solving problems related to current harmonics, series active filters are useful for solving problems related to voltage harmonics.

Power electronics is closely related with sources of power quality problems, for example, residential equipment such as PCs and TVs, office equipment like printers and industrial equipment such as PLCs.

P-Q Theory

"The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory or p-q theory was presented first by (Akagi, Watanabe, & Aredes, 2007). It is valid for transient as well as steady state conditions and it is based on the instantaneous values with or without neutral wire for three phase power system. Firstly, the three phase voltages and current are transformed to α-β-0 coordinates with the help of Clarke's Transformation then the instantaneous values of active and reactive power are calculated.

Inverse Clarke's Transformation is used to find the values of compensating currents from the values of active and reactive powers. Three phase source voltages and load currents are transformed in α-β coordinates using Clarke's theory which are then utilized to calculate instantaneous values of powers. We only require oscillating component of active power for compensation calculations. As the active power consists of oscillating component and average component, low pass filter is used to separate oscillating component.

This theory proves to give very good response for designing power controllers of harmonics compensation. The application of this theory starts from αβ0 transformation which is also known as Clarke transformation. The three-phase voltage and the line currents are transformed into αβ axes by following equations:

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (2.1)$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \quad (2.2)$$

From equations (2.1) and (2.2) the instantaneous real power and instantaneous imaginary power on αβ axes can be expressed as:

$$\begin{bmatrix} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (2.3)$$

As shown in equation (2.3), these two powers consist of average value as well as oscillating values which are to be separated. As shown $\bar{p}$ and $\tilde{p}$ are the average and the oscillating parts of p, whereas $\bar{q}$ and $\tilde{q}$ are the average and the oscillating parts of q. Both the oscillating real $\tilde{p}$ and imaginary $\tilde{q}$ powers represent the presence of harmonics in load current. By knowing the undesirable values of current in real time, they can be eliminated. Our aim is to make source current sinusoidal by eliminating harmonics in load current using shunt active filter.

The equations for compensating current reference in αβ axes can be written as equation (2.4).

$$\begin{bmatrix} i_\alpha' \\ i_\beta \end{bmatrix} = \frac{1}{V\alpha^2 + V\beta^2} \begin{bmatrix} V\alpha & V\beta \\ V\beta & -V\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (2.4)$$

Finally, by Inverse Clarke transformation the compensating current reference are expressed as equation (2.5).

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2.5)$$

Shunt Active Filter

To deal with problems related to current and voltage harmonics, active filters are used. Also, they are capable of dealing with problems related to poor power factor and reactive power compensation. Active filters are classified as shunt, series, and hybrid active filters. Shunt active filters for compensation of current harmonics, series active filters are used for compensation of voltage harmonics, and hybrid active filters for compensation of both current and voltage harmonics (Akagi,1996). In this paper, we will focus on shunt active filter to deal with problems related to current harmonics. A self-controlled dc bus shunt active filter has a topology similar to static compensator which is used in transmission system for reactive power compensation.

Figure 1 shows basic diagram of shunt active filter. As shown, a shunt active filter operates as a current source device injecting the harmonic component generated by the load current but 180° phase shifted. The nonlinear load may be considered as an ac motor driven by a voltage source PWM inverter. The shunt active filter with or without transformer is connected in parallel with the load producing harmonics.

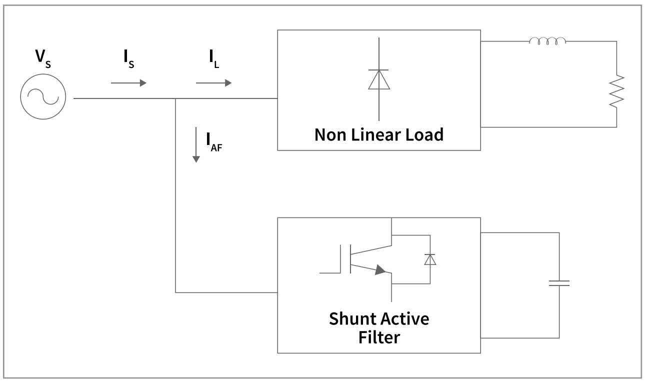


FIGURE 1. Basic shunt active filter

Figure 2 shows the block diagram of shunt active filter showing a voltage fed converter with a PWM current controller and shunt active filter controller. The controller detects the instantaneous load current I_L. Now the controller extracts the harmonic component from load current with the help of low pass filter. The ac inductor L which is placed on the ac side of diode rectifier plays a very important role of limiting the filter current. Shunt active filters can also provide reactive power compensation along with harmonics compensation (Sankaran, 2002).

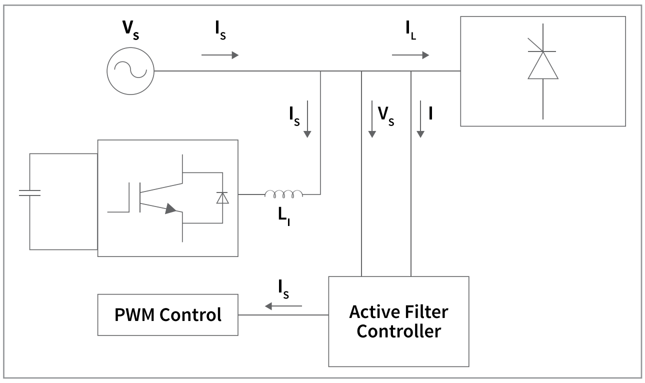


FIGURE 2. Shunt active filter for harmonics compensation

Selection of DC Voltage Reference

To actively control filter current I_c, the dc bus nominal voltage V_{dc} must be greater than or equal to line to line peak voltage i.e. the filter can only compensate when $V_{dc} > V_s$. If we assume that the PWM converter is operating in linear modulation mode then,

$$m_a = \frac{2\sqrt{2}V_{f1}}{V_{dc}} \quad \text{for } m_a = 1 \quad V_{dc} = 2\sqrt{2}V_{f1} \qquad (4.1)$$

In the above equation V_{f1} is the fundamental component at AC side of PWM converter. If the non-linear load is already known then the reference dc bus voltage chosen is the function of load power and the maximum harmonic order which is to be compensated (Colak, Bayindir, Kaplan& Tas,2010).

$$V_{dc} = 2\sqrt{2}V_{(fh)max} \qquad (4.2)$$

where, $V_{(fh)max}$ is the voltage value including harmonics of order to be compensated. In the paper (Krim, 2011). The authors proposed that if the switching frequency is very high then in (4.1) V_{f1}

approximately becomes equal to V_s source voltage, then

$$V_{dc} = 2\sqrt{2}V_s \qquad (4.3)$$

Selection of Filter Inductance L

The value of filter inductance should be kept small enough so that the injected current di/dt is greater than the reference compensating current to track its reference. The value of filter inductance can be mainly found out by reactive power requirement of the system and harmonic cancellations. There are four different approaches proposed by (Krim, 2011). as follows:

1.	$Q_{Lf1} = 3V_sI_{f1} = 3V_s \frac{V_{f1}}{\omega_{Lf}}\left(1- \frac{V_s}{V_{f1}}\right), I_{f1} = \frac{V_{f1}\omega_{mf}}{\omega_{mf\,Lf}}$ where m_f is the modulation ratio of PWM converter.
2.	$L_f = \frac{V_s}{2\sqrt{6}\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ where $\Delta I_{f,\,p\text{-}p,\,max}$ is 15% of the filter current.
3.	$L_{f,min} = \frac{V_{DC}}{8\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ and $L_{f,max} = \frac{V_{DC} - 2\sqrt{2}V_s}{2\,\Sigma_{h=0}^{\infty}\,\omega_h I_h \sqrt{2}}$ where h is the harmonic order.
4.	$L_f = \frac{V_{DC}}{6\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ where $\Delta I_{f,\,p\text{-}p,\,max}$ is maximum ripple current.

TABLE 1. Different methods to find filter inductance L

Based on the above methods we can calculate the filter inductance. Performance of the system can be observed taking different values of filter inductance and the value of filter inductance at which the current harmonics are minimum. Also, we observe that for the low values of filter inductor THD in current are lower due to the presence of high frequency in the signal

Selection of DC Side Capacitor C_{DC}

There are two main purposes of DC side capacitor server:
(i) in steady state it maintains DC voltage and
(ii) during transient period it serves as an energy storage element to supply real power differences.
The choice of DC capacitor is very important and therefore, the DC capacitor must be maintained with the help of a reference value.

When load condition changes, the real power balance between main and the load will be disturbed, which is to be compensated by DC capacitor.

During transients, DC side capacitor helps to maintain variations and ripples in V_{DC}. Change in C_{DC} does not much affect the error in V_{DC} but by change in C_{DC}, the settling time and final value of V_{DC} is affected. So, on the basis of settling time, response time and variation in V_{DC} the final value of C_{DC} is selected. As described by (Krim, 2011). following are the four different methods which can be used for designing C_{DC}.

1.	$C_{DC} = \frac{2\,E_{max}}{V_{DC}^{\ 2} - V_{DC,\,min}^{\ 2}}$ E_{max} is the maximum supplied energy by the capacitor in the worst case.
2.	$C_{DC} = \frac{\pi\, I_{f1,\,rated}}{\sqrt{3}\,\omega V_{DC,\,p\text{-}p,\,max}}$ where $V_{DC,\,p\text{-}p,\,max}$ is the peak to peak voltage ripple.
3.	$C_{DC} = \frac{s}{2\,\omega V_{DC}\,.\,\Delta V_{DC}}$
4.	$C_{DC} = \frac{V_s\sqrt{I_5^2 + I_7^2 - 2\,I_5 I_7\cos(5\alpha\text{-}7\alpha)}}{2\,\omega V_{DC}^{\ 2}\varepsilon}$ or, $C_{DC} = \frac{I_H}{\varepsilon\,\omega_h V_{DC}}$ where I_H is current of the lowest order harmonic.

TABLE 2. Different methods to find DC side capacitance

Simulation Results

Figure 3 shows the MATLAB Simulink model for diode rectifier load as a nonlinear load. Simulation results are obtained and the results are shown in figures 4 and 5. As shown is in figure 4, before compensation the source and the load current contains harmonics due to presence of nonlinear load. Figure 5 shows the results after compensation from shunt active filter. THD of source current reduces from 25.68% to 1.33% after the compensation. It can be seen that the source current becomes sinusoidal after compensation from shunt active filter. Figure 5 also shows that the DC link voltage is maintained at a constant value of 700V which is the reason that filter works appropriately.

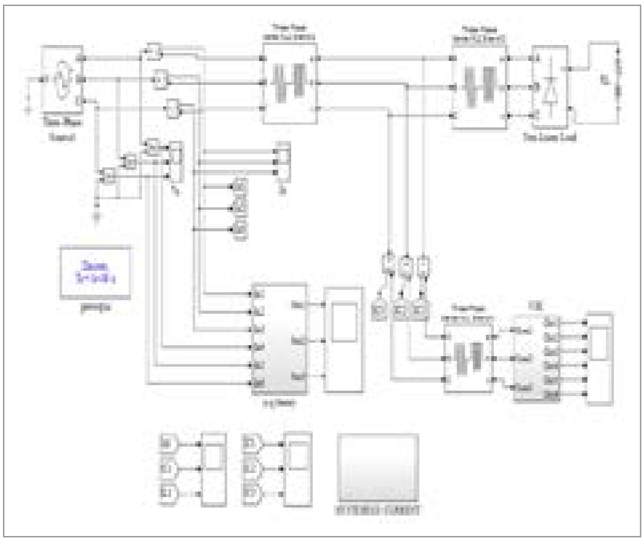
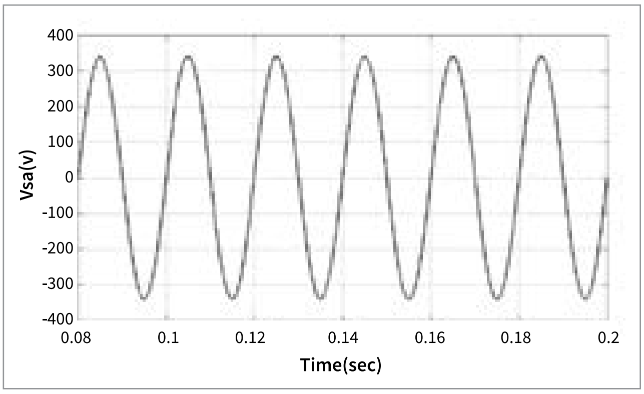


FIGURE 3. Simulink model for diode rectifier load

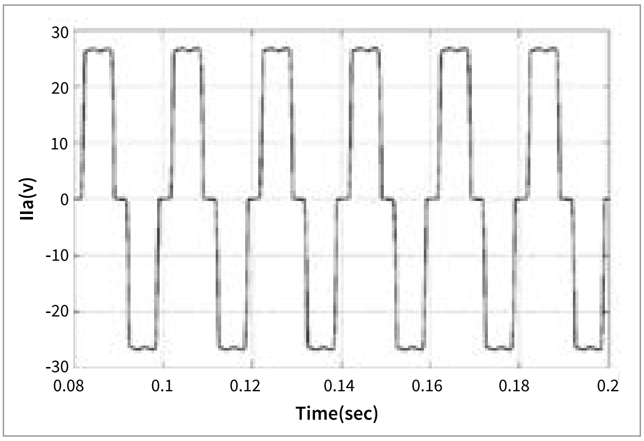
Simulation is done using MATLAB simulation tool. When nonlinear load is connected load due to the presence of harmonics in load the current gets distorted. Reference currents for active filter are generated using p-q theory and then hysteresis current control is used to generate switching signals. Table 3 shows various simulation parameters applied to SAF.

Sr. No.	System Parameter	Values
1	AC Supply	415 V, f = 50 Hz, R_s = 0.4Ω, L_s = 0.1 mH
2	Load Side	R_L = 0.1Ω, L_L = 0.1 mH
3	Filter Side	R_L = 0.4Ω, L_L = 0.3 mH, C_{DC} = 1000 μF
4	PI Controller	Kp = 0.2, Ki = 10
5	DC Side Capacitor Voltage	700 V
6	Diode Bridge Rectifier	R = 20Ω, L = 100 mH
7	DC Side Capacitor	1000μF

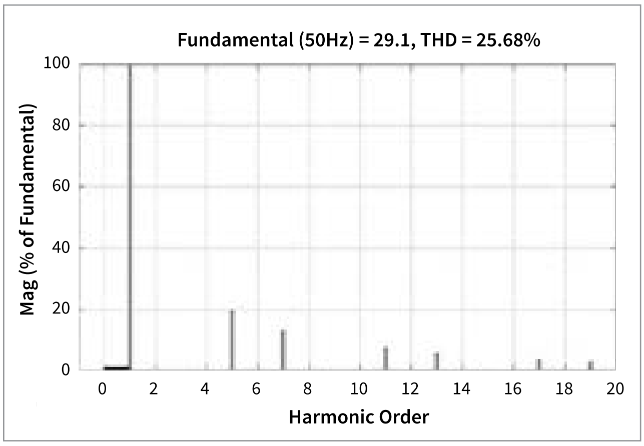
TABLE 3. Various parameters applied to SAF (Diode load)



(a)

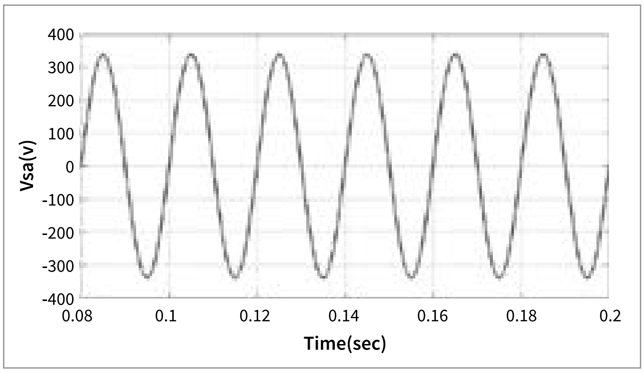


(b)

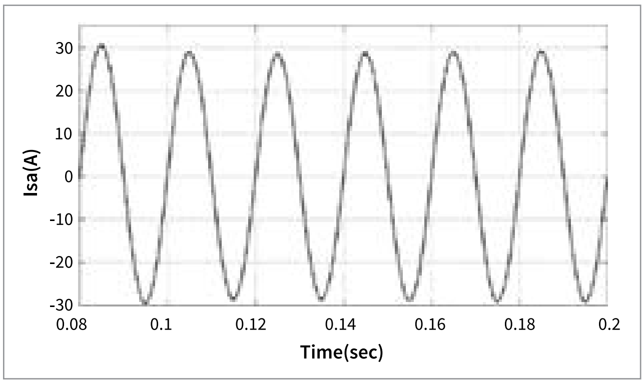


(c)

FIGURE 4. Simulation results of (a) source voltage (b) source/load current (c) THD before compensation for diode rectifier load



(a)



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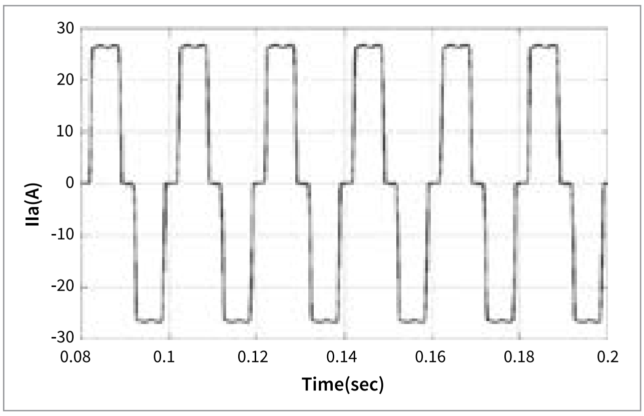
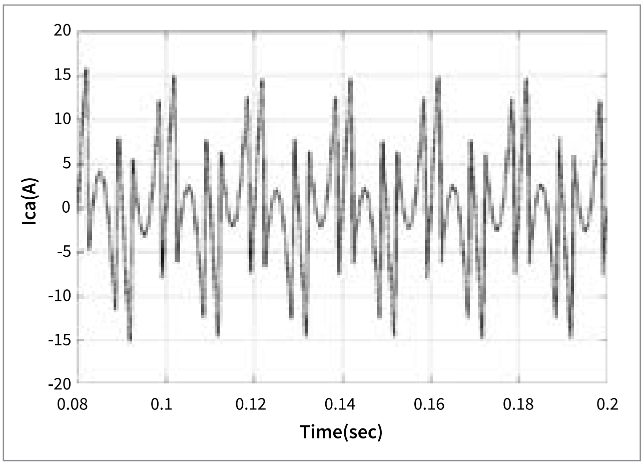
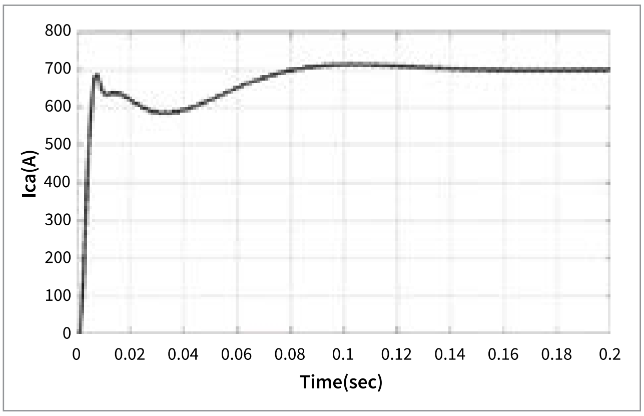


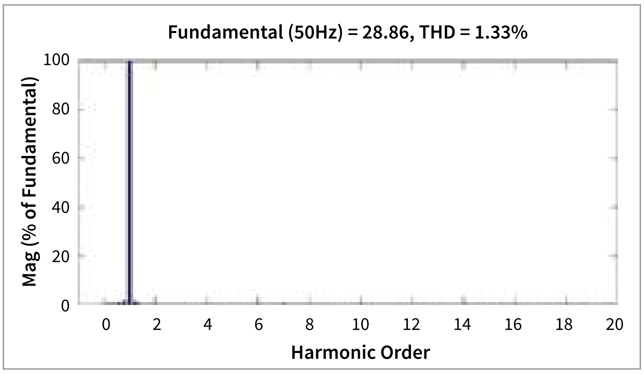
(c)



(d)



(e)



(f)

FIGURE 5. Simulation results of (a) source voltage (b) source current (c) load current (d) filter current (e) DC link voltage (f) THD after compensation for diode rectifier load

A shunt active power filter has been investigated for power quality improvement. The optimum values of Kp and Ki are found to be 0.2 and 10. From the above results of waveforms we can say that harmonics distortion is reduced after connecting shunt active filter. The system parameter selected for simulation are designed which are mentioned in table 3. After compensation, the source voltage and the source current are in phase with each other which means that the harmonics are eliminated from the source current and the power quality if system is thus improved.

Conclusion and Scope for Future Work

Table 4 shows the comparison of simulation result obtained before and after compensation form shunt active filter. Before compensation the harmonics component in source current was 25.68% which was reduced to 1.33% after compensation. PI control based shunt active filter is implemented for harmonic compensation of nonlinear load current. After the results are obtained it is found that shunt active filter is able to mitigate the current harmonics by eliminating the harmonic component in current.

From the study of reference papers, it was found that, better compensation and consequently better power-quality can be obtained by combining active filter with passive filters, that is, using the hybrid approach.

In hybrid filter, shunt or series, active filter is used along with passive filter to obtain better compensation.

Condition in simulation	THD in source current before active filtering	THD in source current after active filtering
Steady state condition (Diode-Rectifier load)	25.68%	1.33%

TABLE 4. Result obtained from simulation of SAF

Nomenclature

PQ – Power Quality

PWM – Pulse Width Modulation

SAF – Shunt Active Filter

THD – Total Harmonic Distortion

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