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Power quality improvement in distribution system based on dynamic voltage restorer using PI tuned fuzzy logic controller

Purpose. *This article proposes a new control strategy for Dynamic Voltage Restorer (DVR) in utility grid for distribution system. The proposed DVR using PI tuned fuzzy logic scheme is based on replacement of conventional DVR and voltage sag compensation in distribution system network.* ***The novelty*** *of the proposed work consists in presenting an enhanced PI tuned fuzzy logic algorithm to control efficiently the dynamic voltage restorer when voltage sag is suddenly occurred.* ***Methods.*** *The proposed algorithm which provides sophisticated and cost-effective solution for power quality problems. Our strategy is based on tuned fuzzy control of reactive powers and also closed loop for harmonic reduction in distribution system. The proposed control technique strategy is validated using MATLAB / Simulink software to analysis the working performances.* ***Results.*** *The results obtained clearly show that DVR using PI tuned fuzzy logic have good performances (sag compensation, harmonic reduction) compared to conventional DVR.* ***Originality.*** *Compensation of voltage sag/ swell in distribution for reactive power and current harmonic reduction by using DVR based PI tuned fuzzy logic controller.* ***Practical value****. The work concerns the comparative study and the application of DVR based on PI tuned fuzzy techniques to achieve a good performance control system of the distribution system. This article presents a comparative study between the conventional DVR control and PI tuned fuzzy DVR control. The strategy based on the use of a PI tuned fuzzy controller algorithm for the control of the continuous voltage sag and harmonic for the distribution network-linear as well as non-linear loads in efficient manner. The study is validated by the simulation results based on MATLAB / Simulink software.* References 27, tables 3, figures 20.

Key words: **dynamic voltage restorer, proportional integral controller, proportional integral tuned fuzzy logic controller, voltage source inverter, pulse-width modulation generator, total harmonic distortion.**

Мета*. У статті пропонується нова стратегія управління пристроєм динамічного відновлення напруги (ДВН) в мережі розподільної системи. Запропонований ДВН, що використовує схему нечіткої логіки з ПІ-налаштуванням, заснований на заміні звичайного ДВН та компенсації провалів напруги в мережі розподільної системи.* ***Новизна*** *запропонованої роботи полягає у поданні удосконаленого алгоритму нечіткої логіки з ПІ-налаштуванням для ефективного управління динамічним відновником напруги при раптовому виникненні провалу напруги.* ***Методи****. Запропоновано алгоритм, який забезпечує складне та економічне вирішення проблем якості електроенергії. Наша стратегія заснована на нечіткому керуванні реактивною потужністю, що налаштовується, а також на замкненому контурі для зниження гармонік в розподільній системі. Запропонована методика управління перевіряється за допомогою програмного забезпечення MATLAB/Simulink для аналізу робочих характеристик.* ***Результати****. Отримані результати чітко показують, що ДВН, який використовує нечітку логіку з ПІ-налаштуванням, має хороші характеристики (компенсація провалів, зниження гармонік) порівняно із звичайним ДВН.* ***Оригінальність****. Компенсація провалів/стрибків напруги у розподільній мережі для зниження реактивної потужності та гармонік струму за допомогою нечіткої логіки з використанням ДВН на основі контролера нечіткої логіки з ПІ-налаштуванням.* ***Практична цінність****. Робота стосується порівняльного дослідження та застосування ДВН на основі нечіткої логіки з ПІ-налаштуванням для досягнення хороших параметрів системи керування розподільною системою. У статті представлено порівняльне дослідження звичайного керуванням ДВН та нечіткого керування ДВН з ПІ-налаштуванням. Стратегія, заснована на використанні алгоритму нечіткої логіки з ПІ-налаштуванням для ефективного керування безперервним провалом напруги та гармоніками для лінійних та нелінійних навантажень розподільчої мережі. Дослідження підтверджено результатами моделювання на основі програмного забезпечення MATLAB/Simulink.* Бібл. 27, табл. 3, рис. 20.

Ключові слова: **динамічний відновник напруги, пропорційно-інтегральний контролер, контролер нечіткої логіки з пропорційно-інтегральним налаштуванням, інвертор джерела напруги, генератор широтно-імпульсної модуляції, повне гармонічне спотворення.**

Introduction. Power quality management has become a crucial challenge in today's electrical power system. Load with increased sensitivity and complexity leads to voltage fluctuation, non-standard current and frequency, thereby lowering the power quality. Even a short term voltage fluctuation results in malfunctioning of the entire distribution system. As a result, it is highly crucial to enhance the power quality, which is considered to be a difficult task for industrial customers as it leads to the failure of variety of sensitive electronic equipment.

The demand for electricity is increasing day by day and the issues associated with transmitting the power through the distribution system are growing as well. Voltage fluctuation is regarded to be the most serious PQ issue that must be addressed. Voltage fluctuation often leads to power distribution system failure or malfunction of a continuous process [1, 2]. The voltage fluctuation issues that cause the system to malfunction are voltage sag, swell, transient disruptions, harmonic distortions, spikes and surges [3]. However, voltage sag and swell are regarded to be the most serious power PQ among them. On the other hand, the magnitude of the voltage is one of the most important elements that determine the quality of electrical power, and it is essential to increase the quality of the power before it is utilized further [4]. A reliable power supply is essential in today's economy, and both power distributors and consumers have realized the value of power quality throughout time. Furthermore, authorities are now very interested in ensuring that power distributors have met their PQ responsibilities or not [5, 6].

The power produced by the power generation system has to be upgraded in order to offer clean and pure power to the power consumers. Previously, generation and transmission systems are responsible for power quality maintenance, but now the primary focus is on the distribution system, which is highly susceptible to electrical breakdowns [7-9]. So that, power distributors have to ensure that the quality of power supplied to the customer have met the operational norms and national standards or not [10].

Therefore, FACTS (Flexible AC Transmission System) controllers are utilized to improve the behavior of the power distribution system [11, 12]. These devices are employed to solve various PQ issues like harmonic distortion and transient stability [13, 14]. FACTS devices such as Static synchronous compensator (STATCOM), Static synchronous series compensator, unified power flow controller (UPFC), interline power flow controller (IPFC) are utilized to deliver high quality electricity. Custom power devices are FACTS devices that have been customized to be employed in electrical distribution systems. Therefore, unified power quality conditioner, active filter, DVR and distribution static synchronous compensator (DSTATCOM) are the commonly employed custom power devices. Such devices are utilized to solve power quality issues in power distribution network [15-18]. Among all custom power devices, DVR has attracted the researchers as it possesses quick response, smaller size and provides cost effective solutions. Therefore, in this work, DVR is utilized to compensate the voltage fluctuations by injecting the voltage in series with the supply from another feeder.

In steady state condition, the DVR has been operated in such a way that it does not receive or supply any real power. However, for any system, the DVR have to maintain minimum VA rating without reducing the compensation capability. To enhance the behavior of the DVR, a control scheme has been utilized [19]. The output generated by the DVR is controlled by the control signal generated by the proportional integral (PI) controller and the switching pulse generated by a Pulse-Width Modulated (PWM) generator. PI follows feedback control strategy and it produces the required control signal for the PWM generator using a weighted sum of error signal [20-23]. The non-linearity of semiconductor components present in the inverter leads to distortions in the output waveform. To solve this problem, a highly qualified power supply with an excellent LC filter unit is utilized [24]. However, the PI controller doesn't respond to the abrupt change in error signal, which is considered to be a serious drawback [25-27]. Therefore, a PI tuned Fuzzy Logic Controller (FLC) is utilized in this work. Here, an inference engine with a rule base of if-then rules is used to determine an output control signal.

In this proposed control scheme, a DVR is employed in this work in order to enhance the PQ in distribution systems. A PI tuned FLC is utilized to control the DVR's inverter. The rest of the work are explained such as modeling of DVR, PI controller and PI tuned FLC.

Proposed control scheme. The proposed block diagram comprises 3 phases AC supply, source inductance, PI tuned FLC, PWM generator, 3 phases Voltage Source Inverter (VSI) and non-linear load. The schematic representation of control scheme is shown in Fig. 1.

Recurrent Neural Network based reference current generation is utilized for effective harmonic elimination. 3 phases VSI for inverting the input DC voltage along with LC filter and AC grid is also employed in STATCOM applications.

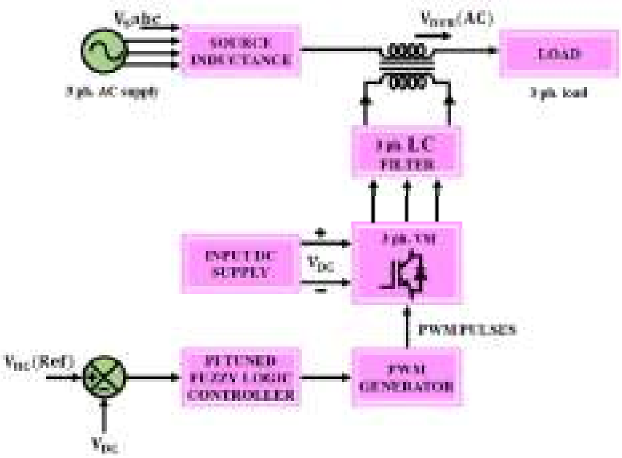

Fig. 1. Schematic representation of control scheme

3 phases AC supply, which is given to the non-linear load, creates voltage oscillations in the distribution system. For reducing the voltage oscillations in the distribution system, the DVR is utilized in this proposed work, which provides sophisticated and cost-effective solution for PQ problems. DVR is a variable or controllable voltage source, which is linked in series with the point of common coupling and the load. DVR controls the active and reactive power, which helps to regulate the load voltage by injecting the suitable voltage during the voltage quality events. The capacitor will be discharged, in order to retain the DC-link voltage as constant. Here an external energy source is needed to deliver reactive power injection. To control the DVR's inverter, the gating pulses for VSI are generated with the aid of PI tuned FLC through which the VSI is controlled and so the reactive power compensation takes place.

Modeling of proposed system.

Dynamic Voltage Restorer (DVR*).* For sag voltage compensation a DVR is widely utilized equipment. The sensitive loads are linked in series to the DVR, which adds the required voltage when needed. It is a cost effective technique, which is used to compensate the voltage sag in small and big loads up to 45 MVA or even more. VSI, a voltage injection device, a filter, an energy storage device and a controlling device are the essential components of DVR. The structure of DVR is illustrated in Figure 2.

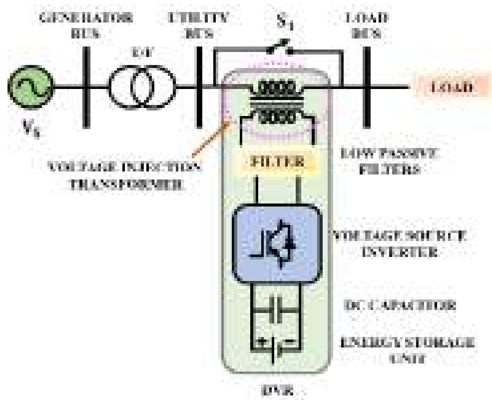

Fig. 2. Structure of DVR

Construction of DVR. The power and control circuits are the two components of DVR. The DVR system injects the control signal, which is made up of complex variables like magnitude, phase shift and the frequency. The switches are utilized in the power circuit in order to produce voltage-dependent control signals.

Energy Storage Unit. Superconducting magnetic energy storage, flywheels, super-capacitors and lead-acid batteries are the equipments, which are used to store energy. The storage unit's major duty is to deliver the required real power when the occurrence of voltage sags. The real power, which is generated by the energy storage device determines the DVR's compensating capability. Instead of employing other storage devices, lead batteries are chosen because they have a fast charging and discharging response time. The rate of discharge which is based on a chemical reaction that controls the amount of internal space available for energy storage.

Voltage Source Inverter. PWM VSI technique is commonly utilized. A DC voltage has been generated using an energy storage instrument. A VSI is utilized, to convert the voltage from DC-AC voltage. To boost the magnitude of voltage at the time of sag, DVR power circuit's step-up voltage injection transformer has been utilized. As a result, a minimal voltage with VSI is sufficient.

Passive Filters. In this technique, the inverted pulse waveform of PWM, which is transformed into a sinusoidal with the utilization of low passive filters. In order to accomplish this conversion in VSI, the higher harmonics are eliminated during the conversion of DC-AC, which also alters the compensated output voltage. Circuit layout of different filters in DVR are indicated in Fig. 3.

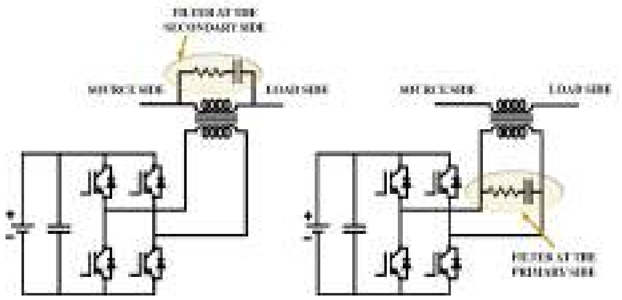

Fig. 3. Different filters in DVR

If the filters are placed on the inverter side, the harmonics are eliminated. The phase shift and voltage drop problems are occurs, when it is placed on the side of inverter. This issue can be resolved by placing the filter on the load side. Because a high valued transformer is required, the transformer's secondary side allows high harmonics currents.

By-Pass Switch. A DVR is equipment which linked in series. If a fault occurs in the downstream, the current flows through the inverter, which creates a fault current. A By-pass switch is utilized for inverter protection. A crowbar switch is commonly utilized to bypass the circuit of inverter. The crowbar identifies current scale, if the current is within the range of parts of inverter. If the current is too large, however, it will be possible to bypass the inverter's components.

Voltage Injection Transformers. The voltage injection transformer consists of two parts, such as primary and secondary side. The primary, which is linked in series with a distribution line and the secondary, which is linked to the DVR's power circuit. One 3 phases (3 ph.) or 1 phase (1 ph.) transformers are utilized for 3 ph. DVRs. However, only one 1 ph. transformer is utilized for 1 ph. DVRs. At the point of contact between three 1 ph. transformers and a 3 ph. DVR, a «Δ–Δ» type connection is employed.

The voltage level, which is delivered by the filtered output of VSI to a required level usually simulates the circuit of DVR from the setup transformer's transformation system. The pre-examined as well as significant values are winding ratios, which are determined by the needed voltage at the secondary side of voltage. The current on primary side with ratio of higher frequency affects the inverter circuit parts and the winding ratio's higher cost with higher frequency currents also affect the inverter circuit parts. When calculating the DVR's operating efficiency, the transformer value is a crucial factor. The upward distribution transformer, which is influenced by the transformer's winding ratio. As a result, the DVR rewards the arrangement of positive and negative segments.

PI controller. The effectiveness of the PI controller in controlling the steady state error as well as its simple instigation are the reasons for its widespread use. However, this controller has the drawback of not being able to increase the system's transient response. As indicated in Fig. 4, the PI controller's equation (1) has the control output which is given to the PWM generator is denoted as *U*, the proportional and integral gains, which are denoted as K_P and K_I, these gains are dependent on the system variables and the error signal is denoted as ε:

$$U(t) = K_P \cdot \varepsilon(t) + K_I \cdot \int_0^t \varepsilon(t)\mathrm{d}t \ . \tag{1}$$

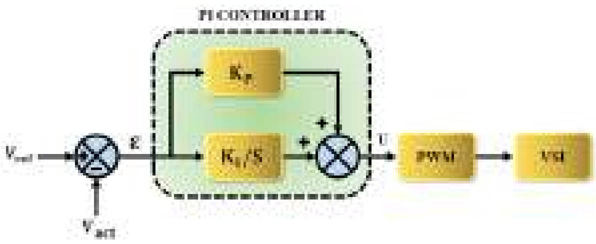

Fig. 4. Block diagram of PI controller

The PI controller creates a pole in the whole feedback loop, which causes the root locus to change. In terms of analysis, the pole causes a change in the response of control scheme. The end result is a decrease in steady state error. The constants K_P and K_I, on the other hand, control the system's stability and transient response in (2).

$$K_P \in \left[K_{P\min}, K_{P\max}\right] \quad \text{and} \quad K_I \in \left[K_{I\min}, K_{I\max}\right]. \tag{2}$$

The minimum as well as maximum constants of PI are estimated in practice using experimentation and iterative methods. As a result, the expert's knowledge is required for the design of a PI controller. The control system becomes unstable if the constants of compensator exceed the permitted values. The tuning of instantaneous parameter constants occurs after the domain of the PI constants has been determined. Depending on the error signal ε, the parameter constants has been adjusted. The constants K_P and K_I are varies to ensure that the system's steady state error is kept to a minimal, if not zero.

PI tuned fuzzy controller. The drawback of PI controller is that it is incapable of reacting to abrupt changes in the error signal ε since it determines only error signal's instantaneous value without taking into account the change in the error signal's the rise and fall, which is the error signal's derivative $\Delta\varepsilon$. To overcome this issue, a fuzzy based PI is utilized as it is indicated in Fig. 5. The control signal's output, which is determined by an inference engine with a rule base of if then rules, which is shown in equation (3):

$$\text{if } \varepsilon \text{ and } \Delta\varepsilon, \text{ then } K_P \text{ and } K_I. \quad (3)$$

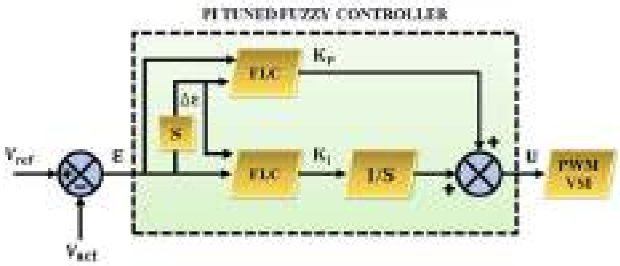

Fig. 5. Block diagram of PI tuned FLC

The constants K_P and K_I are changed by the rule base, which is based on the error signal ε and the change in error $\Delta\varepsilon$. Trial-and-error procedures are utilized to structure and determine the rule basis.

The fuzzy subsets of all the parameters for the inputs ε and $\Delta\varepsilon$ are specified as (*NB*, *NM*, *NS*, *Z*, *PS*, *PM*, *PB*). The fuzzy subsets employs a membership function of «Z»-shaped on the left, triangular shaped on the middle, as well as the «S»-shaped on the right are taken into consideration. The input membership function curves, which are represented in Fig. 6.

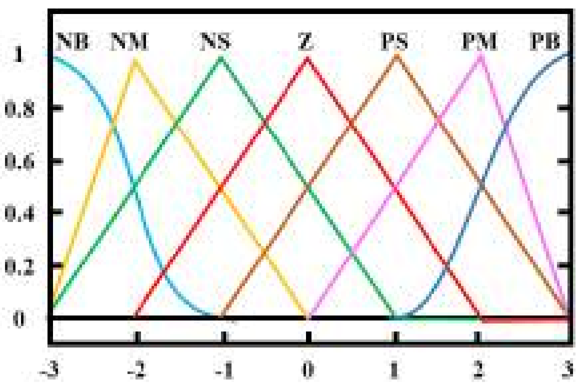

Fig. 6. Input membership function curve

The fuzzy subsets of output parameters K_P and K_I only have a membership function of triangular form, which is represented in Fig. 7. The fuzzy control rule, which is based on the modelling of long-term practical experience of operators, however, the rules were established by the repetitive simulation by means of a PI controller. The fuzzy control rules for the output parameters K_P and K_I are represented in Tables 1, 2.

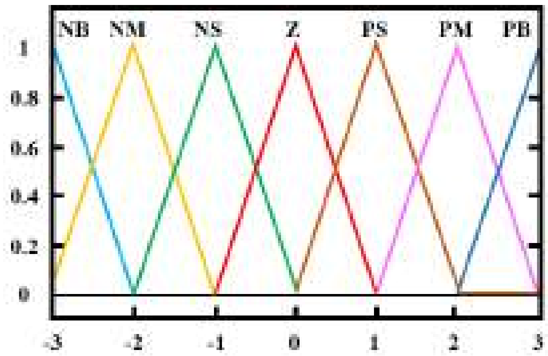

Fig. 7. Output membership function curve

Table 1

Fuzzy control rules for K_P

$\varepsilon/\Delta\varepsilon$	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
NB	*PB*	*PB*	*PM*	*PM*	*PS*	*PS*	*Z*
NM	*PB*	*PB*	*PM*	*PM*	*PS*	*Z*	*NS*
NS	*PM*	*PM*	*PM*	*PS*	*Z*	*NS*	*NM*
Z	*PM*	*PS*	*PS*	*Z*	*NS*	*NM*	*NM*
PS	*PS*	*PS*	*Z*	*NS*	*NS*	*NM*	*NM*
PM	*PS*	*Z*	*NS*	*NM*	*NM*	*NM*	*NB*
PB	*Z*	*NS*	*NS*	*NM*	*NM*	*NB*	*NB*

Table 2

Fuzzy control rules for K_I

$\varepsilon/\Delta\varepsilon$	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
NB	*NB*	*NB*	*NB*	*NM*	*NM*	*NS*	*Z*
NM	*NB*	*NB*	*NM*	*NM*	*NS*	*Z*	*PS*
NS	*NM*	*NM*	*NS*	*NS*	*Z*	*PS*	*PS*
Z	*NM*	*NS*	*NS*	*Z*	*PS*	*PS*	*PM*
PS	*NS*	*NS*	*Z*	*PS*	*PS*	*PM*	*PM*
PM	*NS*	*Z*	*PS*	*PM*	*PM*	*PB*	*PB*
PB	*Z*	*NS*	*PS*	*NM*	*PB*	*PB*	*PB*

Results and discussions. The behavior of proposed control scheme is simulated through MATLAB software. To rectify the PQ issues, a DVR is utilized in this work, which provides sophisticated and cost-effective solution for PQ issues. To control the DVR's inverter, a PI based FLC is utilized in order to generate the required injected voltage, through which the reactive power compensation takes place. The specifications, which are used for DVR is represented in Table 3.

Table 3

Specifications of DVR

Specifications	Values
Source voltage	415
Line resistance	0.1 Ω
Line inductance	0.5 mH
Turns ratio of series transformer	1:1
DC bus voltage	120 V
DC capacitor	220 μF
Filter	L_F = 3 mH, C_F = 1 μF
Line frequency	50 Hz
Switching frequency	10 kHz

The waveforms of AC source voltage and current are illustrated in Fig. 8, 9 respectively. From the voltage waveform, it is noticed that the input source voltage of 415 V is retained as constant. When this input voltage of 415 V is fed to the non-linear load, the harmonics are occurred in the current waveform.

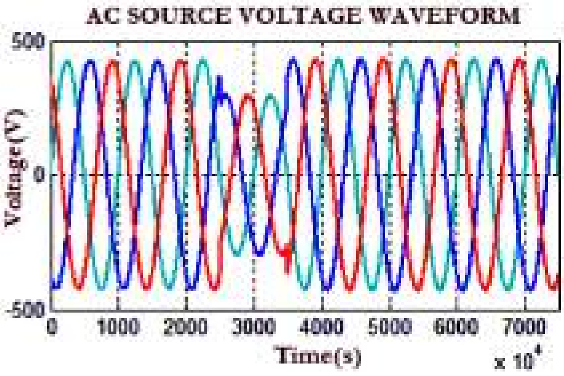

Fig. 8. AC source voltage waveform

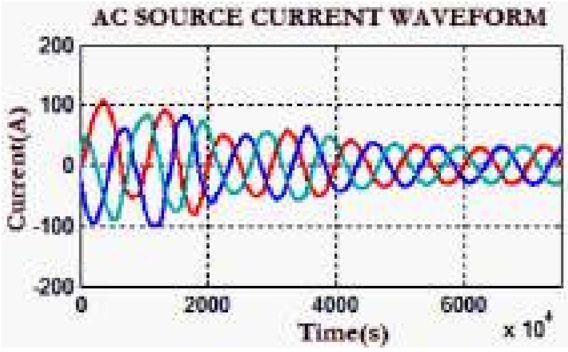

Fig. 9. Waveform of AC source voltage

The waveforms of input AC source voltage and current using DVR are illustrated in Fig. 10. When the input voltage of 415 V is fed to the non-linear load, the harmonics are removed with the utilization of DVR. Thus, it is observed that the waveform becomes sinusoidal by using DVR.

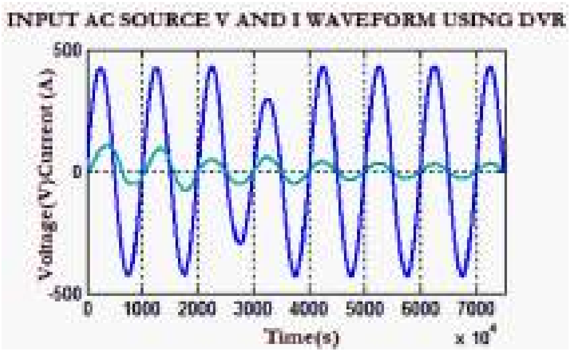

Fig. 10. Input AC source *V* and *I* waveform using DVR

The waveforms of reference and actual voltages of DVR are illustrated in Fig. 11, 12 respectively. The actual and reference voltages are analogized with the aid of PI tuned FLC, through which the gating pulses are generated to control the inverter of DVR.

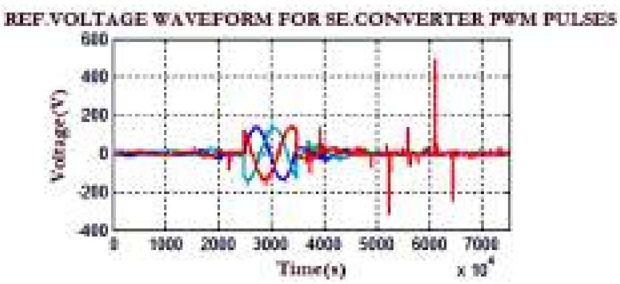

Fig.11. Reference voltage waveform of DVR

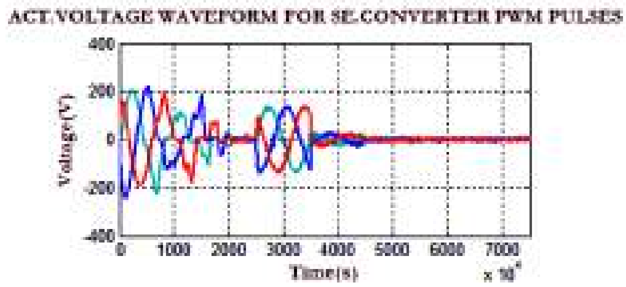

Fig. 12. Actual voltage waveform of DVR

The DC-link voltage waveform is represented in Fig. 13. When the DVR is controlled, the DC-link voltage of 900 V is attained. The occurrence of voltage fluctuations in the initial stage is eliminated and retained as constant after the time of 0.7 s.

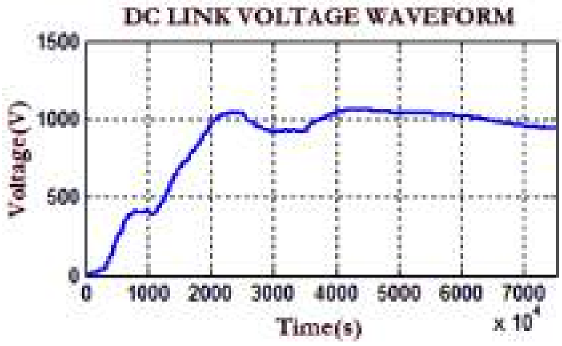

Fig. 13. DC-link voltage waveform

The waveforms of load voltage and current using DVR are illustrated in Fig. 14, 15 respectively. The occurrence of fluctuations in the load voltage and current are minimized after the time 0.2 s with the utilization of DVR. With the assistance of PI tuned FLC, the inverter in the DVR is controlled. Thus the voltage and current become sinusoidal in nature.

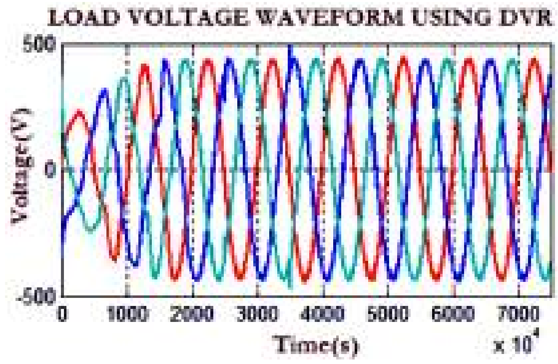

Fig. 14. Waveform of load voltage using DVR

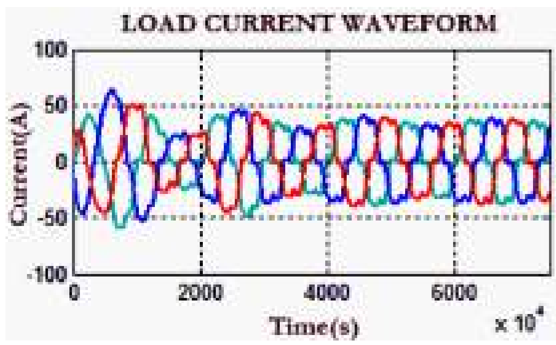

Fig. 15. Waveform of load current using DVR

The waveforms of real and reactive power are illustrated in Fig. 16, 17 respectively. The waveforms have shown that the reactive power compensation is achieved after the time of 0.5 s with the aid of DVR by minimizing the power quality issues.

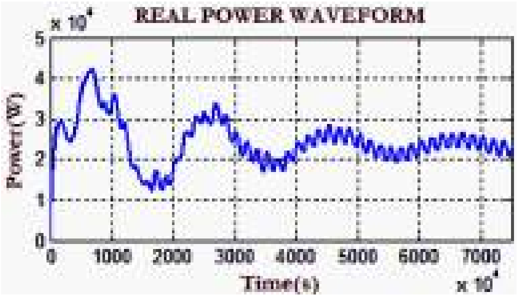

Fig. 16. Waveform of real power

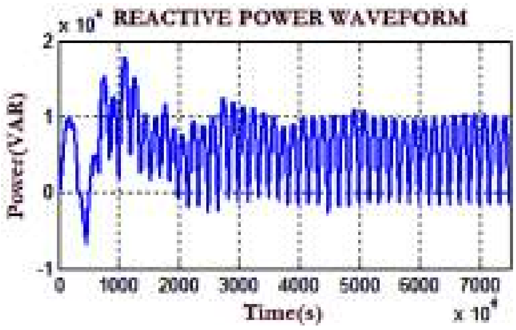

Fig. 17. Waveform of reactive power

The waveform of power factor is illustrated in Fig. 18. When supplying the input voltage to the non-linear loads, certain power quality issues are occur, which are overcome by implementing the DVR. Thus it assists in attaining the UPF through the reactive power compensation. From this waveform, it is noted that the UPF is attained after the time 0.3 s.

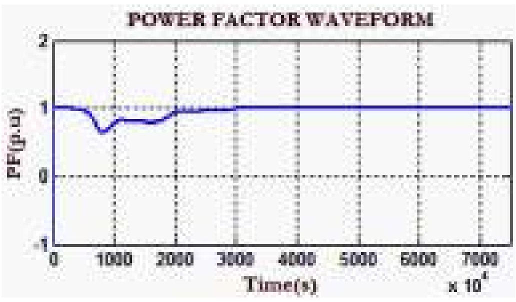

Fig. 18. Waveform of power factor

The waveform of total harmonic distortion (THD) with the utilization of PI tuned FLC is illustrated in Fig. 19. From the above graph, it is noted that the THD of 4.1 % is attained for the PI tuned FLC.

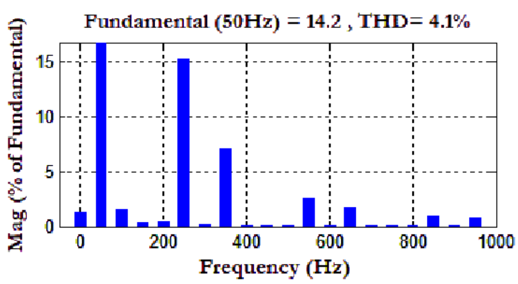

Fig. 19. Waveform of THD

The comparative analysis of THD is illustrated in Fig. 20. The THD of PI tuned FLC is which is comparatively better than the THD values 4.1 %, of FLC and PI. Thus, it is observed that the PI tuned FLC gives better performance than the FLC and PI controllers in the minimization of THD.

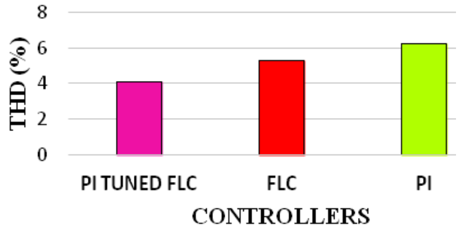

Fig. 20. Comparative analysis of THD

Conclusions.

This paper describes the control strategy of DVR which offers a self-sufficient solution for tackling several issues of power quality. It provides solution for different PQ issues like voltage sag/swell compensation and harmonics. The proposed DVR maintains the significant features and eliminates the complexity by using PI tuned FLC. It generates compensating voltages for the control of DVR and handles the error signal resulted due to system disturbances. The entire work is validated through MATLAB simulation. Thus, the proposed method has delivered improved performance in reducing the PQ issues with the minimum THD of 4.1 %.

Conflict of interest. The authors declare that they have no conflicts of interest.

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