Journal of Electrical Engineering

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Adaptive PI Control of Dynamic Voltage Restorer Using Fuzzy Logic

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Abstract – PI controller is very common in the control of DVRs. However, one disadvantage of this conventional controller is the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters or operating conditions. To overcome this problem, an adaptive PI controller using fuzzy logic is proposed. The controller is composed of fuzzy controller and PI controller. According to the error and error rate of the control system and fuzzy control rules, the fuzzy controller can online adjust the two parameters of the PI controller in order to be adapted to any variations in the operating conditions. The simulation results have proved that the proposed control method greatly improves the performance of the DVR compared to the conventional PI controller.

Keywords: PI, Adaptive fuzzy PI, Fuzzy controller, DVR, Voltage sags, Voltage swells.

I. Introduction

Due to the increased use of a large numbers of sophisticated electrical and electronic equipment, such as computers, programmable logic controllers, variable speed drives, and so forth, proliferation of highly sensitive end-user devices is starting to draw attention of both end customers and suppliers to the question of power quality [1]. Faults at either the transmission or distribution level may cause voltage sag or swell in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Voltage sags can occur at any instant of time, with amplitudes ranging from 10 – 90% and a duration lasting for half a cycle to one minute [2]**.** Further, they could be either balanced or unbalanced, depending on the type of fault and they could have unpredictable magnitudes, depending on factors such as distance from the fault and the transformer connections. Voltage swell, on the other hand, is defined as a sudden increasing of supply voltage up 110% to 180% in RMS voltage at the network fundamental frequency with duration from half a cycle to 1 minute [2]. Voltage swells are not as important as voltage sags because they are less common in distribution systems. Voltage sag and swell can cause sensitive equipment (such as found in semiconductor or chemical plants) to fail, or shutdown, as well as create a large current unbalance that could blow fuses or trip breakers. These effects can be very expensive for the customer, ranging from minor quality variations to production downtime and equipment damage [3].

There are many different methods to mitigate voltage sags and swells, but the use of a DVR is considered to be the most cost efficient method [4].

The most common choice for the control of the DVR is the so called PI controller since it has a simple structure and it can offer relatively a satisfactory performance over a wide range of operation. The main problem of this simple controller is the correct choice of the PI gains and the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters and operating conditions. Therefore, online tuning process must be performed to insure that the controller can deal with all the variations in the system.

Artificial Intelligence (AI) techniques such as neural networks, fuzzy logic (FL) and genetic algorithms (GA) are gaining increased interest nowadays. A lot of techniques have been proposed to tune the gains of PI controller based on AI techniques: Self tuning fuzzy logic technique is one of these methods proposed for the online adaptive tuning of PI controller. In such application, the controller gains are online tuned with the variation of system conditions. The advantage of these techniques is that they are model free strategies because they use the human experience for the generation of the tuning law.

This paper introduces Dynamic Voltage Restorer (DVR) and its operating principle, also presents the proposed controller which is a combination of fuzzy and PI controllers. Then, simulation results using MATLAB-SIMULINK, provide a comparison between the proposed and the conventional PI controllers in terms of performance in voltage sag/swell compensation when the power system impedance changes from very low (stiff power system) to relatively high (weak power system). At the end, discussions of the results and conclusion are given.

II. Dynamic Voltage Restorer (DVR)

A Dynamic Voltage Restorer (DVR) is a series connected solid state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996 [4]. It is normally installed in a distribution system between the supply and the critical load feeder. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load [5]. There are various circuit topologies and control schemes that can be used to implement a DVR [6, 7]. In addition to its main task which is voltage sags and swells compensation, DVR can also added other features such as: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations [8].

The general configuration of the DVR consists of a voltage injection transformer, an output filter, an energy storage device, Voltage Source Inverter (VSI), and a Control system as shown in Figure 1.

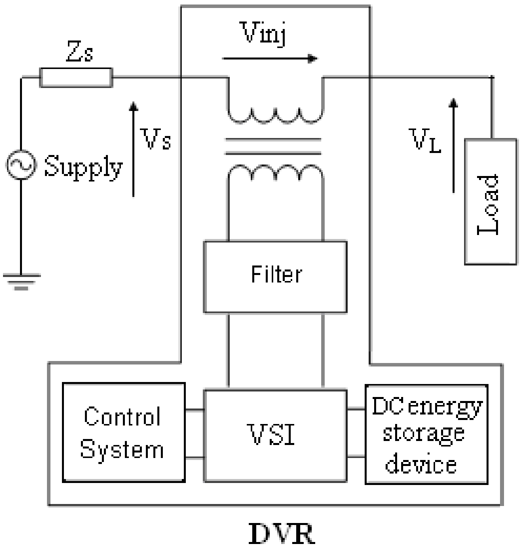


Fig. 1. DVR general configuration

II.1 Voltage Injection Transformer

The basic function of this transformer is to connect the DVR to the distribution network via the HV-windings and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. The design of this transformer is very crucial because, it faces saturation, overrating, overheating, cost and performance. The injected voltage may consist of fundamental, desired harmonics, switching harmonics and dc voltage components. If the transformer is not designed properly, the injected voltage may saturate the transformer and result in improper operation of the DVR [9].

II.2 output Filter

The main task of the output filter is to keep the harmonic voltage content generated by the voltage source inverter to the permissible level (i.e. eliminate high frequency switching harmonics).It has a small rating approximately 2% of the load VA [10].

II.3 Voltage Source Inverter

A VSI is a power electronic system consists of switching devices (IGCTs, IGBTs, GTOs), which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSI is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing [11].

II.4 DC Energy Storage Device

The DC energy storage device provides the real power requirement of the DVR during compensation. Various storage technologies have been proposed including flywheel energy storage [12], super-conducting magnetic energy storage (SMES) [13] and Super capacitors [14, 15]. These have the advantage of fast response. An alternative is the use of lead-acid battery [16, 17]. Batteries were until now considered of limited suitability for DVR applications since it takes considerable time to remove energy from them [18]. Finally, conventional capacitors also can be used [19, 20].

II.5 Control system

The aim of the control system is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The control system of the general configuration typically consists of a voltage correction method which determines the reference voltage that should be injected by DVR and the VSI control which is in this work consists of PWM with PI controller. The controller input is an error signal obtained from the reference voltage and the value of the injected voltage (Fig. 2). Such error is processed by a PI controller then the output is provided to the PWM signal generator that controls the DVR inverter to generate the required injected voltage.

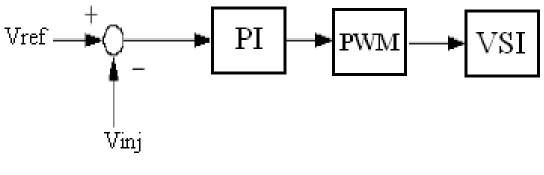


Fig.2. Classical PI controller

III. Operating Principle of DVR

The basic function of the DVR is to inject a dynamically controlled voltage V_{inj} generated by a forced commutated converter in series to the bus voltage by means of a voltage injection transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage V_L. This means that any differential voltages caused by disturbances in the ac feeder will be compensated by an equivalent voltage. The DVR works independently of the type of fault or any event that happens in the system. For most practical cases, a more economical design can be achieved by only compensating the positive and negative sequence components of the voltage disturbance seen at the input of the DVR (because the zero sequence part of a disturbance will not pass through the step down transformer which has infinite impedance for this component).

The DVR has two modes of operation which are: standby mode and boost mode. In standby mode (V_{inj}=0), the voltage injection transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation, because the individual inverter legs are triggered such as to establish a short-circuit path for the transformer connection. The DVR will be most of the time in this mode. In boost mode (V_{inj}>0), the DVR is injecting a compensation voltage through the voltage injection transformer due to a detection of a supply voltage disturbance.

IV. Voltage Reference Calculation Method

There are lots of methods for DVR voltage correction generating reference voltage that DVR must inject it into the bus voltage [21-27]. The strategy of voltage reference calculation used in this work is shown in Figure 3.

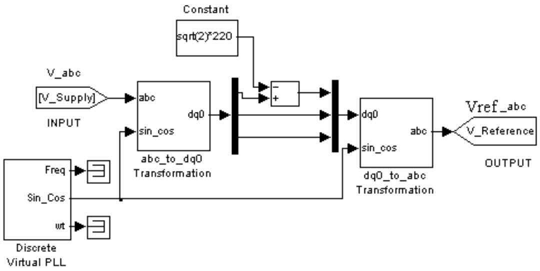


Fig. 3. SIMULINK model of SRF method for voltage reference calculation

Figure 3 shows the basic control scheme and parameters that are measured for control purposes. When the supply voltage is at its normal level the DVR is controlled to reduce the losses in the DVR to a minimum. When voltage sags/swells are detected, the DVR should react as fast as possible and inject an ac voltage into the grid. It can be implemented using the synchronous reference frame (SRF) technique based on the instantaneous values of the supply voltage. The control algorithm produces a three phase reference voltage to the PWM inverter that tries to maintain the load voltage at its reference value. The voltage sag/swell is detected by measuring the error between the d-voltage of the supply and the d-reference value. The d-reference component is set to a rated voltage. The MATLAB/Simulink environment is a useful tool to implement this method (SRF) because it has many tool boxes that can be used easily. The SRF method can be used to compensate all type of voltage disturbances, voltage sag/swell, voltage unbalance and harmonic voltage, but in this work we have studied only voltage sag/swell. The difference between the reference voltage and the injected voltage is applied to the VSI to produce the load rated voltage, with the help of pulse width modulation (PWM) through the PI controller.

V. Conventional PI Controller

The reason behind the extensive use of proportional integral (PI) controller is its effectiveness in the control of steady-state error of a control system and also its easy implementation. However, one disadvantage of this conventional compensator is its inability to improve the transient response of the system. The conventional PI controller (Fig.4) has the form of Eq. (1), where U is the control output which is fed to the PWM signal generator. K_P and K_I are the proportional and integral gains respectively, these gains depend on the system parameters. ε is the error signal, which is the difference of the injected voltage to the reference voltage.

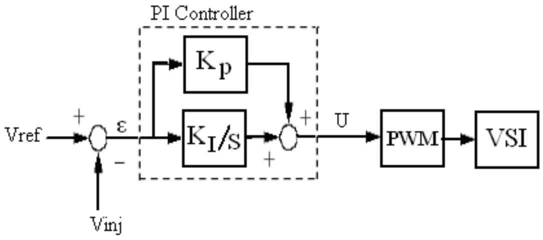


Fig. 4. Control of the injected voltage using conventional PI controller

$$U(t) = K_P \varepsilon(t) + K_I \int_T \varepsilon(t) d(t) \qquad (1)$$

Equation (1) shows that the PI controller introduces a pole in the entire feedback system, consequently, making a change in its original root locus.

Analytically the pole introduces a change in the control system's response. The effect is the reduction of steady-state error. On the other hand, the constants K_P and K_I determine the stability and transient response of the system, in which, these constants rely on their universe of discourses:

$K_P \in [K_P\text{min}, K_P\text{max}]$ and $K_I \in [K_I\text{min}, K_I\text{max}]$.

Where the values of the minimum and maximum proportional and integral constants (gains) are practically evaluated through experimentation and using some iterative techniques. This makes the design of the conventional PI controller dependent on the knowledge of the expert. When the compensator constants exceed the allowable values, the control system may come into an unstable state. After the determination of the domain of the proportional and integral constants, the tuning of the instantaneous values of the constants takes place. Depending on the value of the error signal, ε, the values of the constants adjusts formulating an adaptive control system. The constants K_P and K_I changes to ensure that the steady-state error of the system is reduced to minimum if not zero.

VI. Adaptive Fuzzy PI Controller

The disadvantage of PI controller is its inability to react to abrupt changes in the error signal, ε, because it is only capable of determining the instantaneous value of the error signal without considering the change of the rise and fall of the error, which in mathematical terms is the derivative of the error signal, denoted as $\Delta\varepsilon$. To solve this problem, an adaptive fuzzy PI control as it is shown in Fig 5 is proposed. The determination of the output control signal, is done in an inference engine with a rule base having if-then rules in the form of

IF ε AND $\Delta\varepsilon$, THEN K_P AND K_I

With the rule base, the values of the constants K_P and K_I are changed according to the value of the error signal, ε, and the rate-of-error, Δε. The structure and determination of the rule base is done using trial-and-error methods and is also done through experimentation.

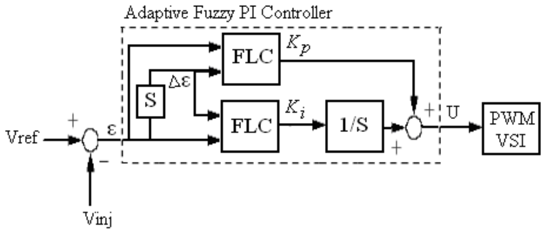


Fig.5. PI gains online tuning by fuzzy logic controller

The basic representation of the fuzzy logic controller (FLC) is given by figure 6.

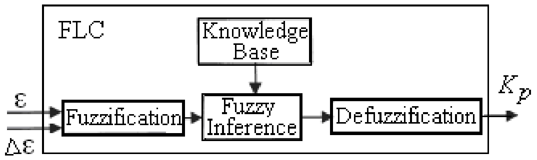


Fig. 6. Schematic of FLC

The MATLAB/SIMULINK implementation of the adaptive fuzzy PI controller for one phase is shown in figure 7.

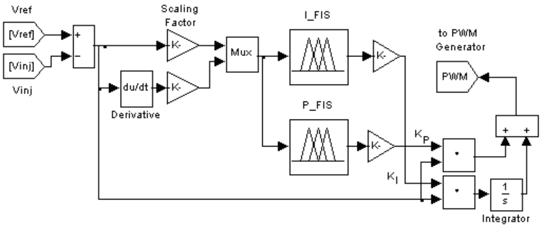


Fig. 7. SIMULINK model of the proposed controller

All the variables' fuzzy subsets for the inputs ε and Δε are defined as (NB, NM, NS, Z, PS, PM, PB). Taking into account of the coverage, sensitivity, robustness of universe, the fuzzy subsets of the membership functions use "Z"- shaped membership function in the left, triangular membership function in the middle, and "S"-shaped membership function curve in the right [28]. The membership functions and initial universes of the inputs are illustrated in Figure 8. For the output variables Kp and Ki, the fuzzy subsets of the membership functions have a triangular shape only as it is illustrated in Figure 9. The fuzzy control rule is the modelling of the experience of operators' (experts) long-term practical accumulation, but in this work the establishment of the rules has been set relying on repetitive simulation using conventional PI controller. Tables 1 and 2 illustrate the fuzzy control rules for the output variables Kp and Ki.

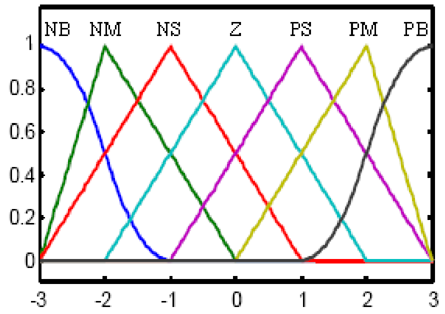


Fig.8. Membership function curves of the inputs ε and Δε

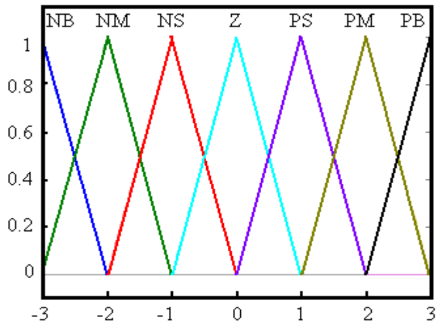


Fig.9. Membership function curves of the output K_p and K_i

Table 1: Fuzzy control rules for K_p

ε /Δε	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

ε /Δε	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

VII. Simulation

Line voltage notch (Notching) is a dip in the supply voltage appears in the line voltage waveform during normal operation of power electronic devices when the current commutates from one phase to another. During this notching period, there exists a momentary short - circuit between the two commutating phases, reducing the line voltage; the voltage reduction is limited only by the supply impedance (IEEE Sdt 519-1992). In this scope, we have made the comparison of the performance of the DVR when it uses the conventional PI controller then when it uses the adaptive fuzzy PI controller in two cases; the first case where the power system is supposed to be stiff which means a very low supply impedance, in this case notching does not appear. The second case where the power system is supposed to be weak which means a relatively high supply impedance, in this case notching does appear.To illustrate the Performance Improvement of Dynamic Voltage Restorer in voltage sags and swells mitigation using the proposed controller in the two cases, a simple distribution network is simulated using MATLAB/SIMULINK software (fig.10). A DVR is connected to the system through a series transformer with a capability to insert a maximum voltage of 100% of the phase to ground system voltage. In the following simulations, the main characteristics of the DVR are set as: voltage source full-bridge IGBT based inverter controlled with PWM signal generator with commutation frequency of 12kHz, capacitor energy storage bank 8.8 mF, coupling transformer ratio 1:1, nominal dc link voltage 850V, LC output filter values C_f=220 μF in series with a damping resistance R_d = 0.5 Ω, L_f =0.6mH, source voltage 220Vrms and source frequency of 50 Hz. The load is a non linear load composed of a diode rectifier feeding an RL load where L=60mH and R=10/3 Ω connected to the DVR through a very small inductance L_{in} = 0.1mH. The power system (supply) is simulated as an ideal voltage source in series with impedance as shown in Figure 10. The impedance of the supply is considered to be a pure inductance Ls since in practical situation the supply resistance is very low compared to the inductance. For the first case where the power system is considered stiff Lc=19.26$10^{-7}$ H and for the second case where power system is considered weak Lc=16.5$10^{-5}$ H. this values of Lc are not given randomly but we have taken into consideration the IEEE 519-1992 standard which divide power system in five groups. Our considered stiff power system is located in the first group and the weak power system in the fourth group. The tuning of the PI is made such to have high transient speed and to have very low tracking error for the fundamental (50 Hz), with K_p = *250* and K_i = 135.

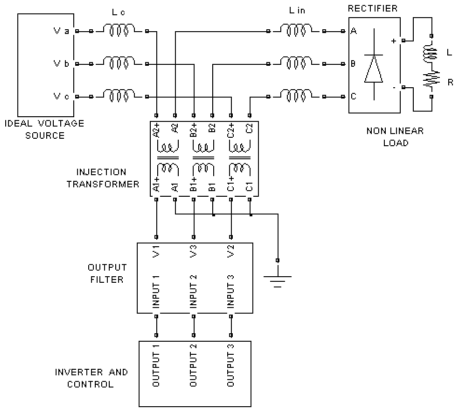


Fig. 10. SIMULINK Model of the simulated system

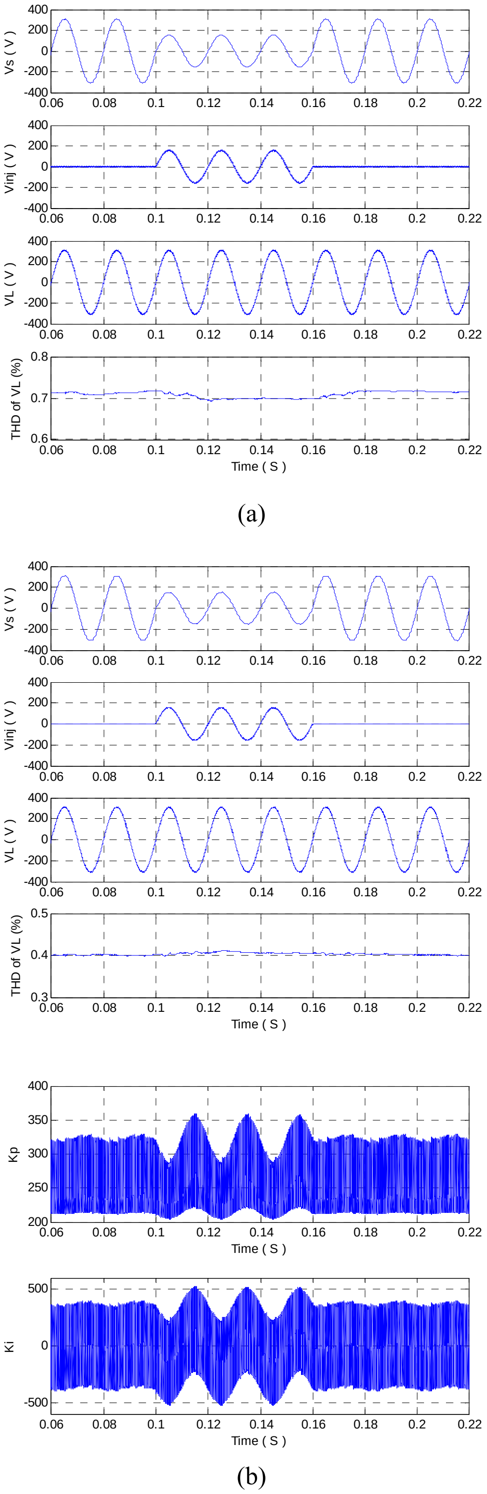


Fig. 11. Comparison of the performance of DVR using PI and adaptive fuzzy PI controllers under the compensation of a 50 % sag in stiff power system. a) PI. b) Adaptive fuzzy PI.

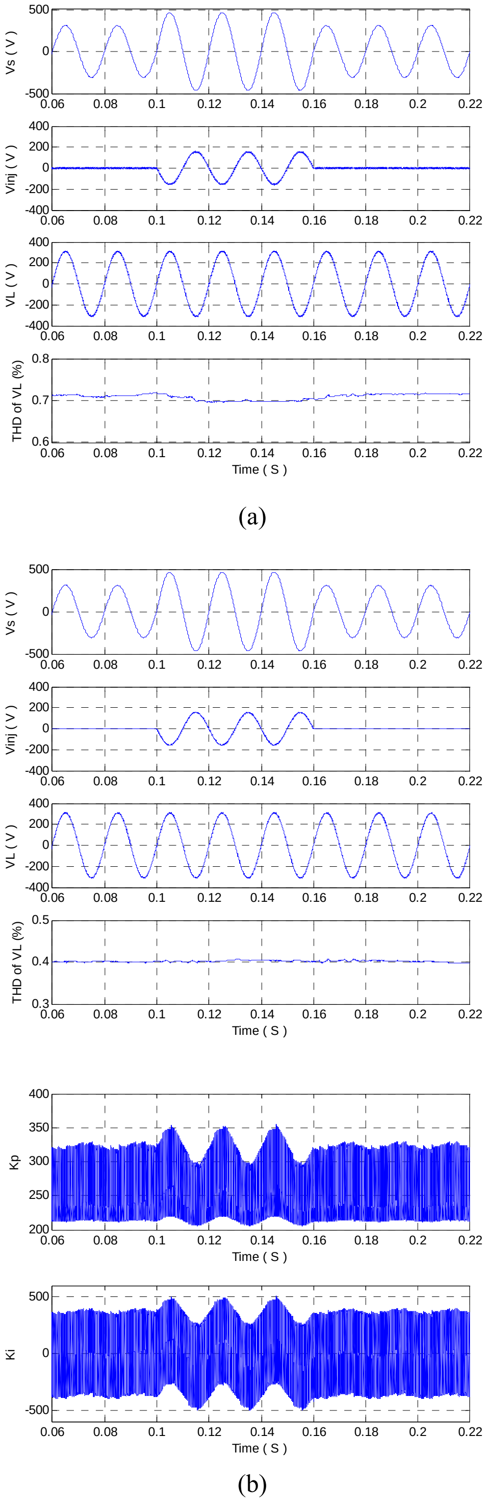
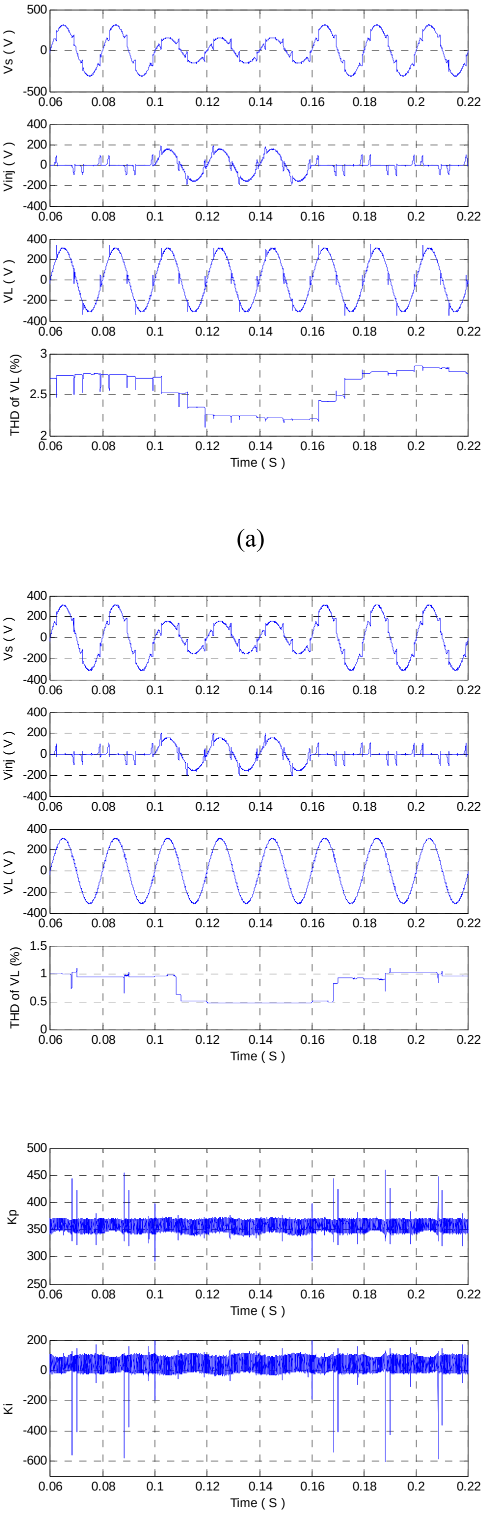


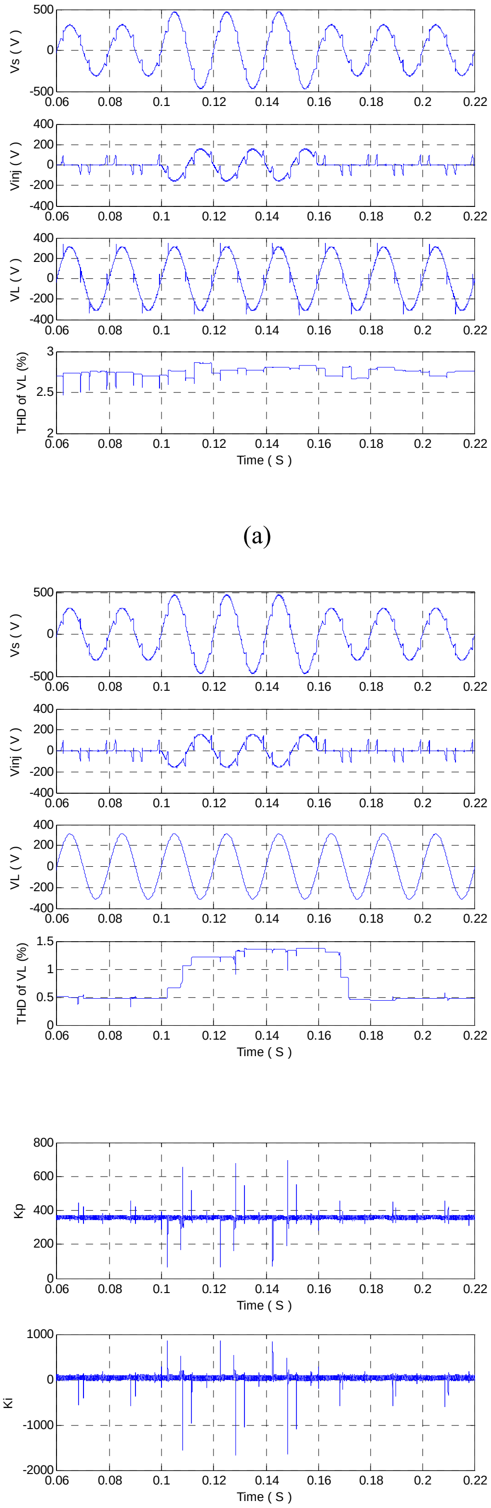
Fig. 12. Comparison of the performance of DVR using PI and adaptive fuzzy PI controllers under the compensation of a 50 % swell in stiff power system. a) PI. b) Adaptive fuzzy PI.



(a)

(b)

Fig. 13. Comparison of the performance of DVR using PI and adaptive fuzzy PI controllers under the compensation of a 50 % sag in weak power system. a) PI. b) Adaptive fuzzy PI.



(a)

(b)

Fig. 14. Comparison of the performance of DVR using PI and adaptive fuzzy PI controllers under the compensation of a 50 % swell in weak power system. a) PI. b) Adaptive fuzzy PI.

Three-phase 50% voltage sag/swell is simulated and for simplification the results of only one phase are shown. Voltage sag/swell is initiated at 100 ms and it is kept until 160 ms, with total voltage sag/swell duration of 60ms. For the first case (stiff power system) the results are shown in Figures 11 and 12 and as we can see notching does not appear in supply voltage (Vs). In this case, both conventional PI and adaptive fuzzy PI (AF PI) controller performs well but the proposed controller presents slight performance improvement with respect to PI controller (THD = 0.4 for AF PI and THD= 0.7 for PI). The gains K_p and K_i for AF PI controller are not constant, K_p varies between 200 and 350 and K_i varies between -500 and 500. For the second case (weak power system) the results are shown in Figures 13 and 14 and notching appears in supply voltage (Vs). In this case, the conventional PI does not compensate notching and voltage notch appears in load voltage (VL) (Fig. 13 (a) and 14(a)). The THD of the load voltage reaches 2.8 but it still satisfies the standard IEEE 519-1992 (THD < 3). We can get rid of notching by increasing the value of L_{in} with a decrease in the voltage across the load which could not be accepted. The proposed adaptive fuzzy PI controller performance is shown in Figures 13(b) and 14(b). As we can see, the FA PI controller compensates notching and the load voltage (VL) is almost free from voltage notch with THD much better than that obtained using PI controller. The gains K_p and K_i for AF PI controller also in this case are not constant, K_p varies between 340 and 375 with picks that can reach 700 and K_i varies between -60 and 130 with picks that can reach -1700. As a result, it is evident that the proposed adaptive fuzzy PI controller has improved the performance of DVR in the two studied cases in addition to its ability to compensate notching in the case of a weak power system. In general, the proposed controller also solves the problem of traditional PI tuning.

VIII. Conclusion

DVRs are effective custom power devices for voltage sags and swells mitigation; they inject the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. In the present paper a better controller for dynamic voltage restorers was proposed. The proposed controller combines fuzzy logic to classical PI controller to adjust online the PI gains. According to the obtained simulation results of voltage sag and swell compensation in a stiff and weak power system. The main advantage of adaptive fuzzy PI controller over the classical one (PI) is its ability to compensate notching when the DVR is connected to a weak power system. In addition, adaptive fuzzy PI controller improves performance of the DVR and solves the problem of PI tuning.

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