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UKF based estimation approach for DVR control to compensate voltage swell in distribution systems

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KEYWORDS

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Abstract The Dynamic Voltage Restorer (DVR) is identified as the best solution for mitigation of voltage sag and swell related problems in the much taped distribution system. The compensation performance of the DVR very much depends on its control algorithm. In the paper, an estimation method based on Unscented Kalman Filter (UKF) is proposed for mitigating the voltage swell concern. The proposed UKF based estimation technique is used to assist the control algorithm for generating reference signals of Voltage Source Converter (VSC) of DVR. DVR presents the compensation voltage as output which is included in the connected line. With this estimation method, voltage swell issues are discovered with accuracy and faster performance to retract out the swell problem in sensitivity load linked distribution systems. In MATLAB/Simulink platform the suggested method is executed and its performance is assessed and contrasted with the Linear Kalman Filter (LKF) and Extended Kalman Filter (EKF).

1. Introduction

Nowadays power quality (PQ) is a crucial issue to companies which are operating in a highly competitive business environment, because it affects the profitability in terms of both time and money. Hence there are always demands for good power quality. But due to the use of modern industrial devices such as semiconductor devices, programmable logic controllers and electronic devices PQ problems have gained more interest. These devices are more sensitive to power quality disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions [11]. Voltage sag/swell is considered as to be the most severe disturbances among them [2]. Voltage sag/swell is characterized by magnitude and duration of sag/swell. Voltage swell is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical magnitudes are between 1.1 and 1.8 up. Swell magnitude is also described by its remaining voltage; in this case, it is always greater than 1.0 [3]. Common causes for voltage swell are switching off a large load, energization of a capacitor bank, etc. [1]. The effect of voltage swell is control delay, tripping, overheating and many times

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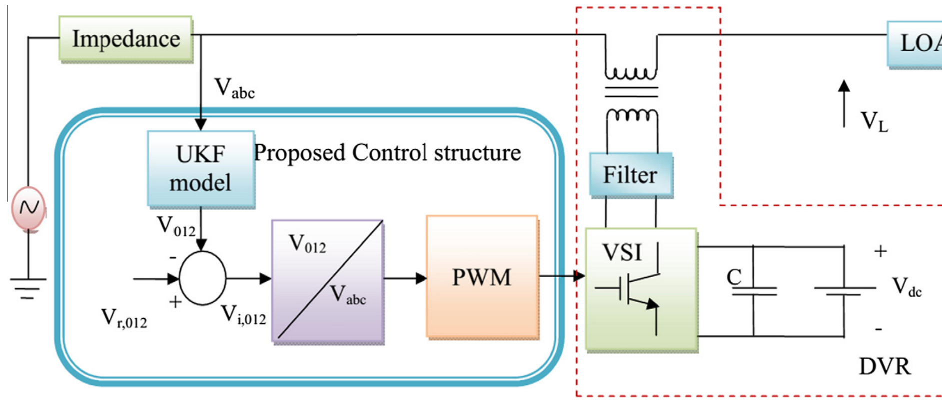

Figure 1 Control structure of proposed system with DVR.

destruction electrical equipments. Several methods are available to prevent equipment malfunction due to voltage swells but the use of custom power service is considered to be the most efficient method [6].

There are many Custom power devices (CPD) which are a powerful tool based on semiconductor switches concept to protect sensitive loads if there is a disturbance from power line. Among the several novel CPD, the Dynamic Voltage Restorer (DVR) is now becoming more established in industry to mitigate the impact of voltage disturbances on sensitive loads [9,7]. DVR is an important tool to mitigate disturbances related to power quality problems in the distribution network. One of the crucial disturbances in the electrical network is voltage swells [8,12]. Generally, a DVR encloses five components: an energy storage system or an alternative power source, a VSC that alters the DC voltage from the energy storage system to the required AC voltage to invalidate disturbances, greatly sags only, a coupling transformer which is series coupled in the feeder, an output filter to retract the harmonics brought in by the PWM process of the VSC and a control approach for VSC [13,4]. Alternatively, the presentation of the DVR very much depends on their control strategies which keep steady voltage magnitude by discovering out the reference voltages for VSC [15]. However, this is only discovered according to the degree of disturbances in supply voltages [16,19]. Accordingly, with the appropriate control approach, it adds three single phase AC output voltages in series with the distribution feeder to prolong the desired amplitude and waveform for load voltage even when the system voltage is unbalance or altered [17]. The DVR maintains the load voltage at a nominal magnitude and phase by compensating the voltage sag/swell, voltage unbalance and voltage harmonics presented at the point of common coupling [5,18].

Various control strategies have been developed to mitigate the voltage sag and swell have been proposed for three phase voltage source PWM converters. They can be divided into two main groups: linear and nonlinear, linear controllers include the ramp-comparison current regulator, Synchronous PI regulator, state feedback regulator, predictive and dead-beat regulator and the hard-switched converter. The neural network and Fuzzy Logic (FL) based regulators belong to the nonlinear controllers. It appears that the nonlinear controller is more suitable than the linear type since the DVR is truly a nonlinear system [20]. The DVR is a nonlinear device due to the presence of power semiconductor switches in the

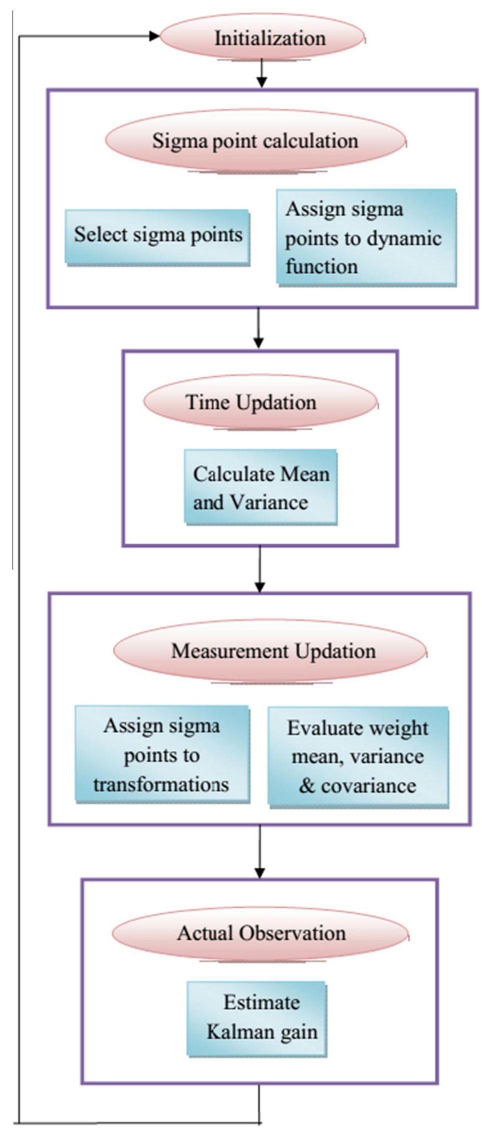

Figure 2 Process for UKF estimation algorithm.

inverter bridge [14]. Detection of voltage swell problem and estimation of reference voltages for VSC in advance carry out a most important role for voltage swell mitigation by

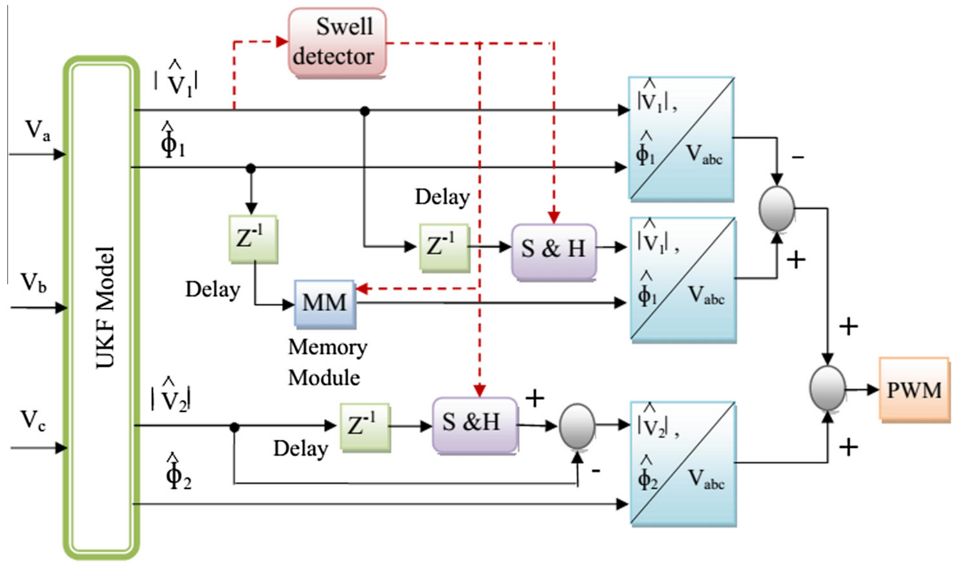

Figure 3 The proposed control scheme aided by UKF model.

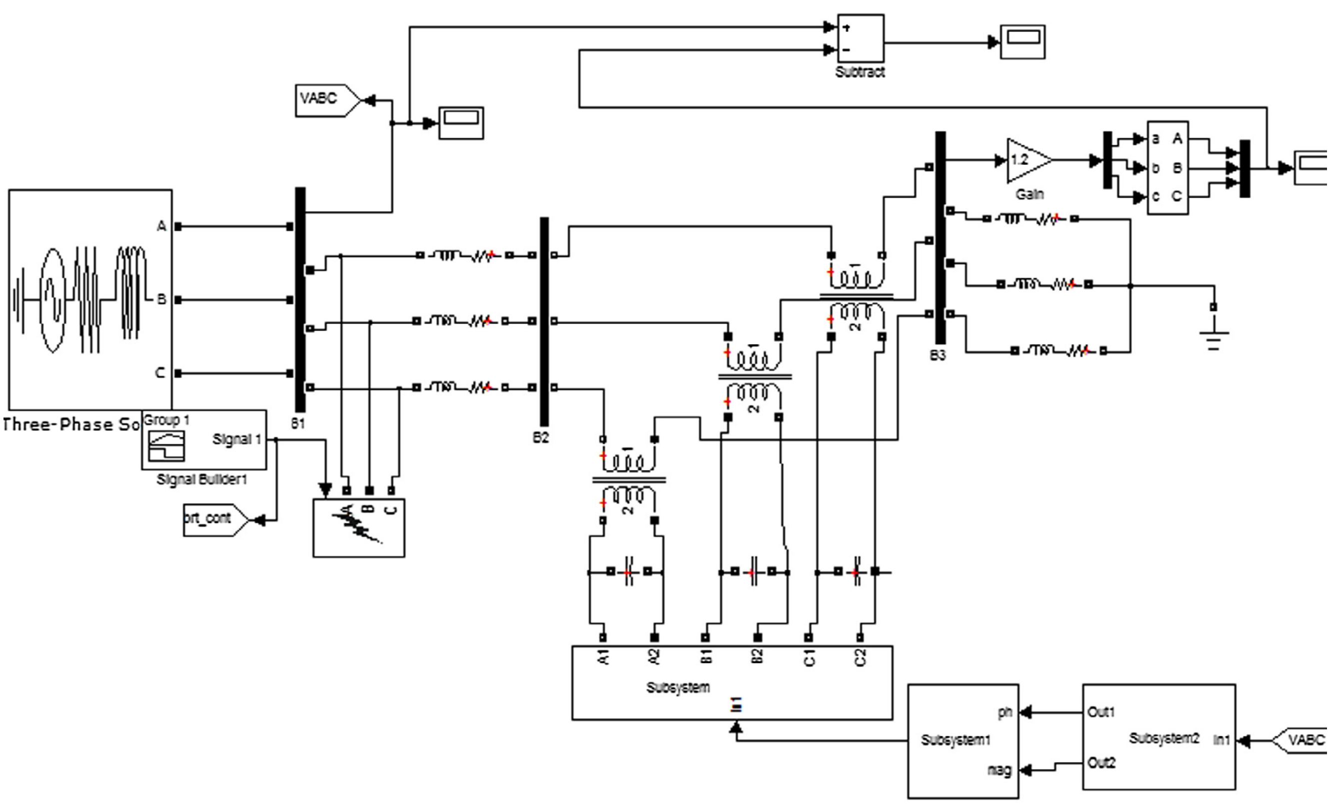

Figure 4 The Simulink model of proposed system.

DVR [10]. In the paper, an UKF based estimation model is employed to assist the control algorithm of DVR. It is applied to estimate the symmetrical components of the supply voltages for finding and helping in compensation of swell. Here, Section 2 discussed the latest research works and the thorough proposed method is precise in the Section 3. The performance of the voltage swells is observed in the Section 4. The last part of the paper is precise in Section 5.

2. Related works

Using DVR, there are many research works offered on voltage sag/swell mitigation in the literature. A few of them are assessed here.

Ramasamy and Thangavel [21] have proposed a photovoltaic fed Dynamic Voltage Restorer (PV-DVR) to mitigate

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Table 1 Implementation parameters.

S. No	Description of parameter	Values
1	Line voltage (V_L)	415 V
2	Phase voltage (V_P)	230 V
3	Frequency (F)	50 Hz
4	Resistance (R)	31.84 Ω
5	Inductance (L)	0.139 H

deep voltage sags, voltage swells and outages on a low voltage residential distribution system during both daytime and night-time. However, the reduction of energy consumption was always desirable for the reduction of panel tariff and global warming gases.

Using DVR an auxiliary control approach for downstream fault current interruption has been suggested by Ajaei et al. [22] in a radial distribution line. The suggested controller increased the voltage-sag compensation control of the DVR. It did not need phase-locked loop and separately controlled the magnitude and phase angle of the injected voltage for each phase.

An easy generalized algorithm has been proposed by Kanjiya et al. [23] based on basic Synchronous Reference Frame (SRF) theory for the generation of instant reference compensating voltages for controlling a DVR. It applied the fundamental positive-sequence phase voltages extorted by sensing only two unbalanced and/or distorted line voltages.

Different voltage injection schemes for DVR have been suggested by Jayaprakash et al. [24] were examined with particular

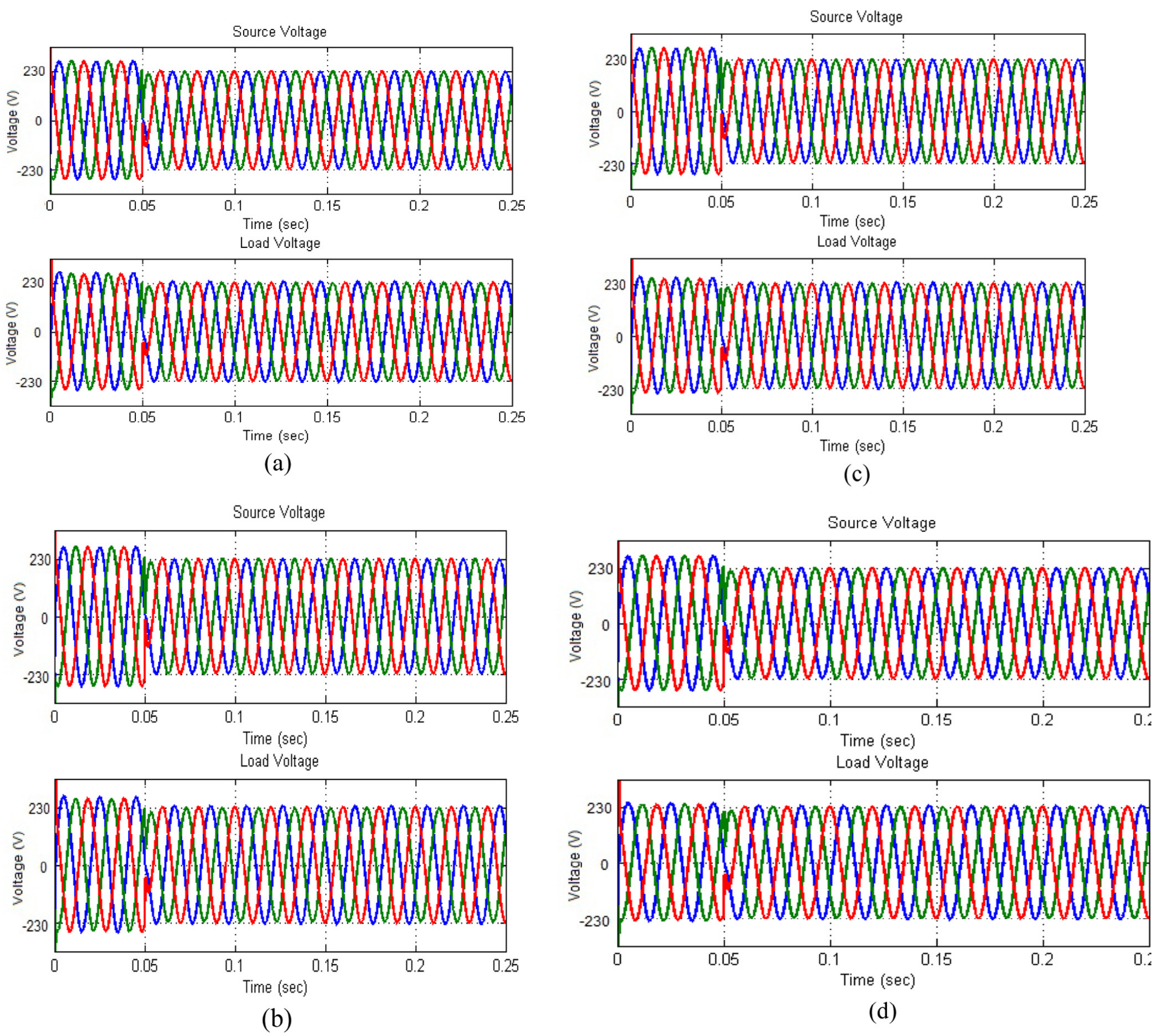

Figure 5 (a) Source and load voltage performance of conventional controller during voltage swell condition; (b) source and load voltage performance of Kalman based DVR controller during voltage swell condition; (c) source and load voltage performance of EKF based DVR controller during voltage swell condition; (d) source and load voltage performance of UKF based DVR controller during voltage swell condition.

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focus employed to minimize the rating of the VSC applied in DVR. A novel control technique was suggested to control the capacitor-supported DVR. With a reduced-rating VSC the control of a DVR was shown. The reference load voltage was estimated by means of the unit vectors. The SRF theory was applied for the change of voltages from rotating vectors to the stationary frame.

Sundarabalan and Selvi [25] have presented the effectual exploitation of DVR for interconnecting the proton exchange membrane fuel cell (PEMFC) stack to the grid based on optimized proportional integral (PI) and fuzzy logic (FL) Controller. The real coded Genetic algorithm (GA) was used to optimize the PI controller parameters. Their designed method also protects the sensitive loads from source side power quality disturbances including short term interruption.

Abdul Rahman et al. [26] have presented for generating the pwm signals, which is mostly analog and not at all computation-intensive. Illustrations were provided in which the swell or sag can be brought down by using the power either from the other two phases or power from the same phase. The emphasis was not to establish the superiority or otherwise these arrangements of diverting power from any one phase to the other phase for mitigating the sag or swell.

There is various control algorithms such as fuzzy logic, deadbeat control and vector control have been used for DVR. To give back the voltage swell is the purpose of these control algorithms. In the uttered control algorithms, fuzzy logic needs the exact determination of fuzzy membership functions and fuzzy rule formulations which are possible by expert's knowledge merely. For discovering out the reference voltages these drawbacks are making the DVR's control algorithm more uncertain. It needs a good recognition technique for any kind of voltage swell disturbance to improve the presentation of the control approach. It is possible to create the reference voltages in lesser time with the good estimation technique only and faster control action is performed. If the estimation is poor, it is impossible to create the exact reference voltages for VSC which formulates the DVR's compensation

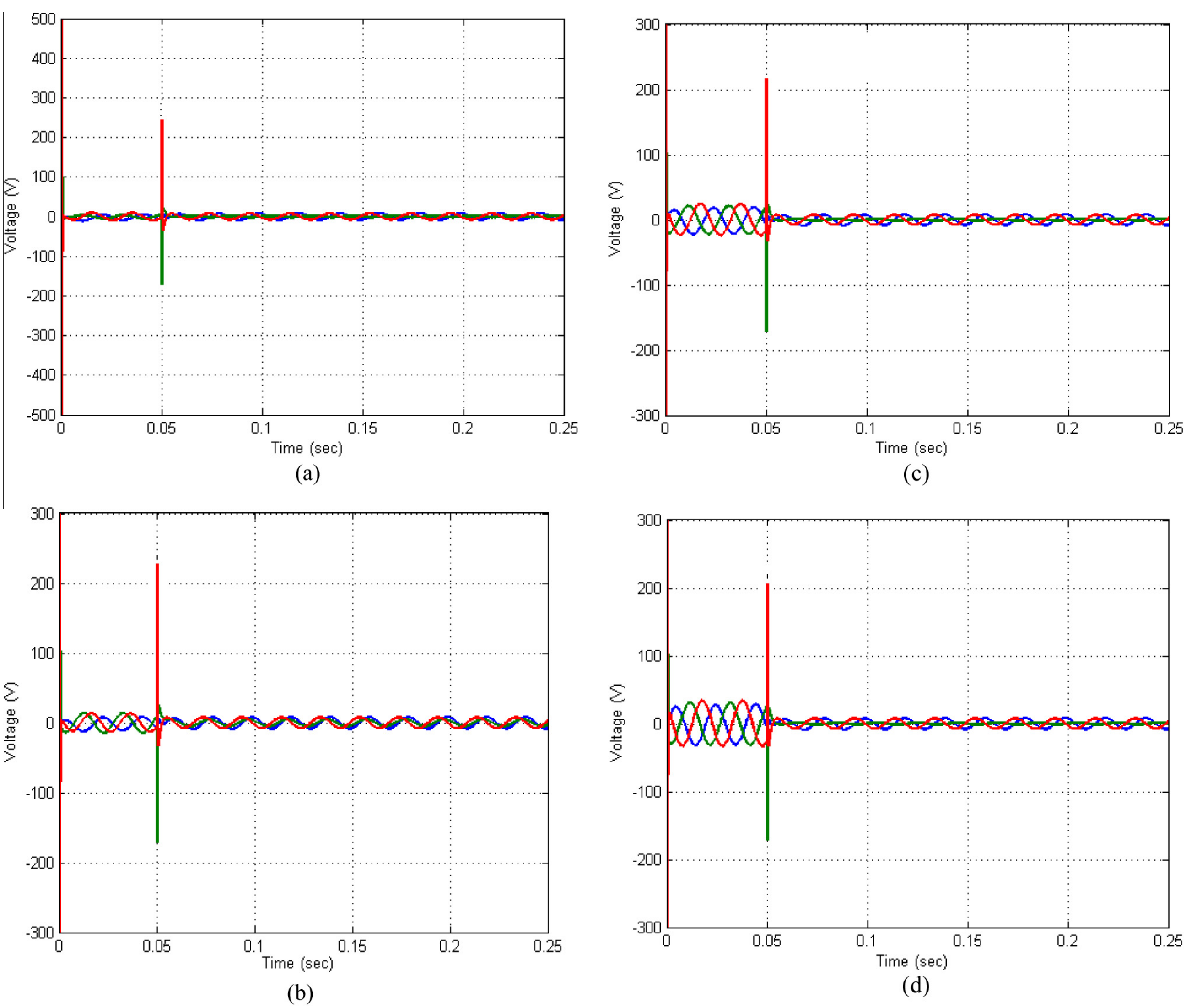

Figure 6 (a) Injected voltage performance of conventional controller during fault; (b) injected voltage performance of Kalman based DVR controller during fault; (c) injected voltage performance of EKF based DVR controller during fault; (d) injected voltage performance of UKF based DVR controller during fault.

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terrible. It demonstrates that various techniques such as least error square digital filter and SRF theory have been introduced for the process of discovering out the reference voltages from the linked work. By employing EKF estimation technique, it offers improved results but it cannot stop to the mark performance as the linearization of the underlying nonlinear model circulates the covariance. These issues in estimating the compensating reference voltages make them uncertain to carry out voltage swell mitigation. Accordingly, it needs good estimation technique for discovering out the voltage swell occurrence in the system for better compensation. In the literature, a very tiny works are presented considering estimating techniques previous to the control algorithm design for voltage swell compensation. Therefore, the above uttered drawbacks have motivated me to do this research work.

3. Overview of Dynamic Voltage Restorer with proposed system

In a distribution network, Dynamic Voltage Restorer (DVR) is a series linked device capable of regulating the load side voltage. The DVR primarily contains an injection transformer, DC charging unit, storage devices, VSI, harmonic filter and control unit correspondingly. A VSI is a power electronic system containing a storage device and switching devices, which can produce a sinusoidal voltage at any necessary frequency, magnitude, and phase angle. For DVR application, the VSI is employed to briefly substitute the supply voltage or to produce the part of the supply voltage which is absent. The purpose of storage devices is to provide the necessary energy to the VSI through a dc link for the generation of injected voltages. Now the energy storage devices are capacitor. The most important task of harmonic filter is to remain the harmonic voltage content produced by the VSI to the acceptable level [27]. Beside to voltage sags and swells compensation, DVR can as well be employed for line voltage harmonic compensation, voltage transient reductions and fault current restrictions. The control unit of DVR is accountable for controlling the compensating voltage generation by controlling the PWM pulses to the gates of semiconductor switches of the VSC. Competent control architecture capable of achieving fast compensation is required to maximize dynamic performance of DVR. In the document, an UKF based estimation technique is suggested for developing the presentation of DVR. The suggested UKF based DVR is employed to alleviate the voltage sags/swell. The suggested control algorithm depends on the symmetrical components of the supply voltages. By the suggested control algorithm the voltage sag/swell distortion is programmed and compensates it before feeding to the load. As a result, any sensitive load connected to it is securely protected. The control and protection unit maximizes the system performance and minimizes the losses connected with the operation of DVR depending upon the operating conditions. The DVR injects a series voltage (V_{inj}) through the injection transformer so that the desired load voltage magnitude (V_l) can be maintained. The series injected voltage of the DVR can be written as

$$V_{inj} = V_s + V_l \tag{1}$$

where V_l and V_s are the desired load magnitude and the source voltage during sags/swells condition. The suggested control algorithm encloses estimation model and control modules which are explicated in the subsequent subsections.

3.1. UKF based DVR control module

In Fig. 1 the block diagram of the proposed control scheme based on UKF model is presented. From the block diagram of the proposed control algorithm, it utters that, UKF model estimates the symmetrical components of the supply voltages and is compared with reference symmetrical components to present the injecting voltage by the DVR such that the detected swell is compensated. The reference symmetrical components are the swell symmetrical components which are discovered by the suggested control scheme as specified in the following subsection.

At present, the estimation of immediate symmetrical components of the supply voltages is implemented by UKF model is explained. The purpose of symmetrical components is performed in this subsection. Initially, to detect them, it is necessary to represent the suggested system in state equations. The state equations are attained from the measured voltage representations in terms of their symmetrical components. With those state equations, state variables are selected and appropriate state vector and measurement vector equations are attained. UKF model estimates the symmetrical components from these state equations.

The measured supply voltages of proposed system can be expressed as the following equation,

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} V_m^a \sin(\omega t + \phi_a) \\ V_m^b \sin(\omega t + \phi_b) \\ V_m^c \sin(\omega t + \phi_c) \end{bmatrix} \tag{2}$$

$$V_a(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \phi_0) \\ V_m^1 \sin(\omega t + \phi_p) \\ V_m^2 \sin(\omega t + \phi_n) \end{bmatrix} \tag{3}$$

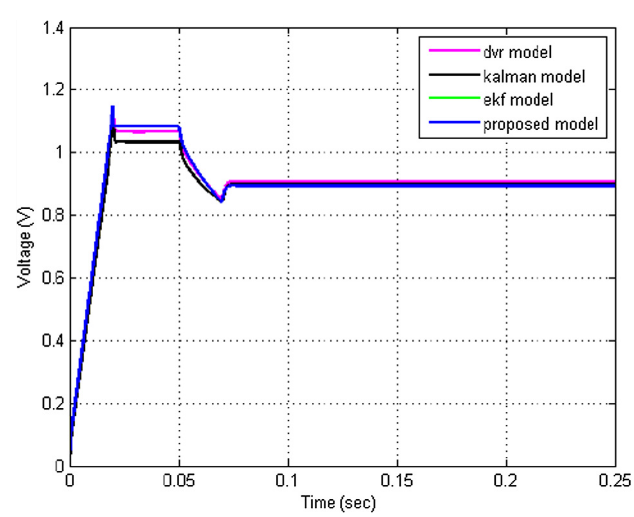

Figure 7 Comparison performance of positive sequence amplitude for all controllers during fault.

$$V_b(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \phi_0) \\ V_m^1 \sin(\omega t + \phi_p - 120) \\ V_m^2 \sin(\omega t + \phi_n + 120) \end{bmatrix} \quad (4)$$

$$V_c(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \phi_0) \\ V_m^1 \sin(\omega t + \phi_p + 120) \\ V_m^2 \sin(\omega t + \phi_n - 120) \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} & h_{15} & h_{16} \\ h_{21} & h_{22} & h_{23} & h_{24} & h_{25} & h_{26} \\ h_{31} & h_{32} & h_{33} & h_{34} & h_{35} & h_{36} \end{bmatrix} \begin{bmatrix} V_m^0 \cos(\phi_0) \\ V_m^0 \sin(\phi_0) \\ V_m^1 \cos(\phi_1) \\ V_m^1 \sin(\phi_1) \\ V_m^2 \cos(\phi_2) \\ V_m^2 \sin(\phi_2) \end{bmatrix} \quad (6)$$

In the above equation, h_{ij} is ith, jth element of the measurement matrix. To select the symmetrical component based functions as state variables, the state vector variables can be expressed as,

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \\ x_6(t) \end{bmatrix} = \begin{bmatrix} V_m^0 \cos(\phi_0) \\ V_m^0 \sin(\phi_0) \\ V_m^1 \cos(\phi_1) \\ V_m^1 \sin(\phi_1) \\ V_m^2 \cos(\phi_2) \\ V_m^2 \sin(\phi_2) \end{bmatrix} \quad (7)$$

From above equation, the measurement equation of the suggested DVR system can be specified in simplified form as,

$$Z(t) = H(t) \cdot X(t) \quad (8)$$

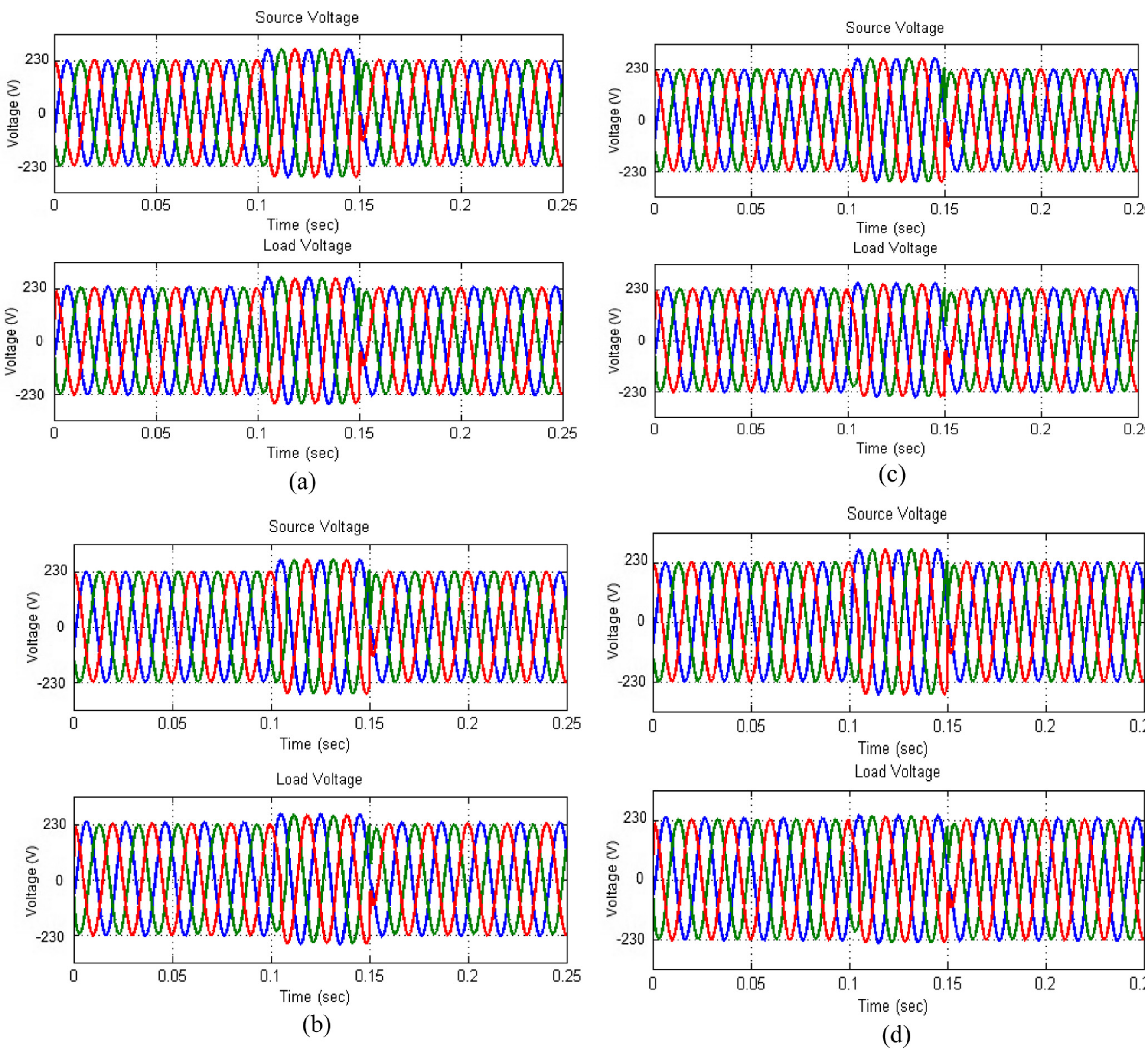

Figure 8 (a) Source and load voltage performance of conventional controller during voltage swell condition; (b) source and load voltage performance of KF based DVR controller during voltage swell condition; (c) source and load voltage performance of EKF based DVR controller during voltage swell condition; (d) source and load voltage performance of proposed controller during voltage swell condition.

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where $Z(t)$ is the measured three phase supply voltage at time instant t. The $H(t)$ is the measurement matrix. Now, let us represent the state variables $X(t)$, in terms of discrete. It is represented as follows.

$$\begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \\ x_4(k) \\ x_5(k) \\ x_6(k) \end{bmatrix} = \begin{bmatrix} V_m^0 \cos(\phi_0) \\ V_m^0 \sin(\phi_0) \\ V_m^1 \cos(\phi_1) \\ V_m^1 \sin(\phi_1) \\ V_m^2 \cos(\phi_2) \\ V_m^2 \sin(\phi_2) \end{bmatrix} \tag{9}$$

where $x_i(k)$ is the kth sample of ith state variable. From Eq. (8), it states that, state variables are the sine or cosine functions of sequence component's amplitude and its phase angles. With this sine and cosine functions in consideration, it can presume that there is a minor change in amplitude and phase angle between successive samples. As a result, the subsequent simplification for the state vector is valid:

$$\begin{bmatrix} x_1(k+1) \\ . \\ . \\ . \\ x. \\ x_6(k+1) \end{bmatrix} \approx \begin{bmatrix} x_1(k) \\ . \\ . \\ . \\ . \\ x_6(k) \end{bmatrix} \tag{10}$$

Then the updating equation of the state variables is expressed as,

$$X(k+1) = X(k) \tag{11}$$

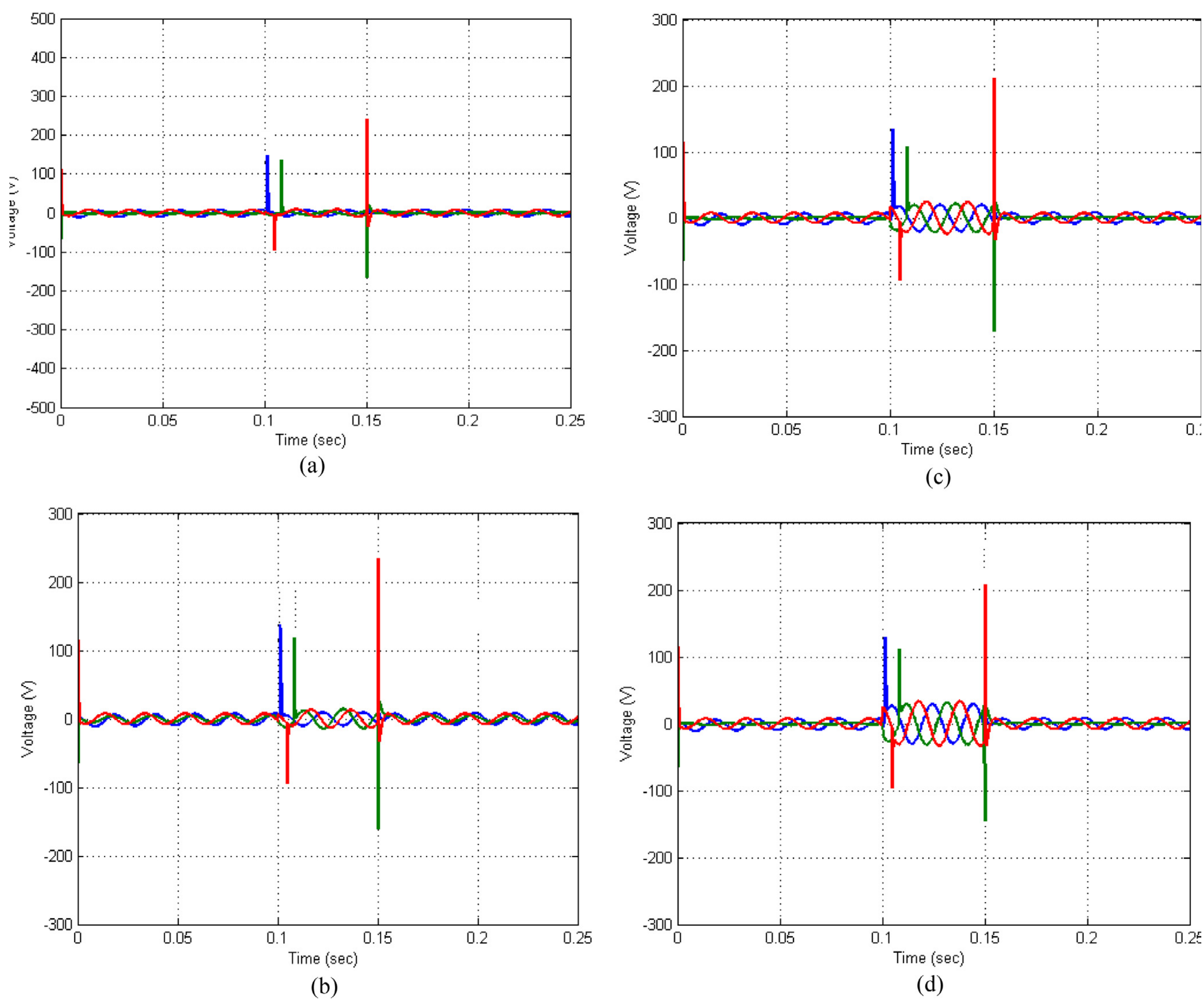

Figure 9 (a) Injected voltage performance of conventional controller during fault; (b) injected voltage performance of KF based DVR controller during fault; (c) injected voltage performance of EKF based DVR controller during fault; (d) injected voltage performance of UKF based DVR controller during fault.

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where $X(k+1)$ and $X(k)$ are the future and present sample of the state vector respectively. Now, from Eqs. (10) and (11), the proposed nonlinear system can be represented as state equations. Therefore, the discrete process and measurement equations of the proposed system are given as,

$$\left.\begin{aligned} X(k+1) &= f[X(k), k] + w(k) \\ Z(k) &= h[X(k), k] + v(k) \end{aligned}\right\} \tag{12}$$

In the above equation, $f[X(k), k]$ and $h[X(k), k]$ are nonlinear vector functions, namely, state matrix and measurement matrix respectively. $v(k)$ is a white noise vector with zero mean and $R(k)$ is as its covariance matrix. $w(k)$ is a vector that describes the state vector response due to a white noise input and has zero mean with $Q(k)$ as its covariance matrix. In the paper, Eq. (11) is processed by UKF model to estimate the state variables of the proposed system and then determine the symmetrical components.

3.1.1. UKF estimation approach

The extended Kalman Filter is probably the most widely used estimation algorithm for nonlinear systems. However, previous experience in the estimation community has shown that the EKF is often difficult to implement, difficult to tune, and reliable only for systems that are almost linear on the timescale of the updates [28]. Many of these difficulties arise from its use of linearization. To overcome this limitation, unscented transformation (UT) is applied to propagate mean and covariance information by nonlinear transformation. It is more accurate, easier to implement, and uses the same order of calculations as linearization. The UKF algorithm consists of three main parts which are sigma point calculations, state prediction and state correction respectively. The Unscented Kalman Filter (UKF), based on UT theory, can be summarized as follows:

3.1.1.1. Initialization. In the process, the filter is initialized. Here, the initial state x_0 is a random vector with the known mean and the covariance is represented as the following,

$$\hat{x}_0 = E[x_0] \tag{13}$$

$$P_0 = E[(x_0 - \hat{x}_0)(x_0 - \hat{x}_0)^t] \tag{14}$$

3.1.1.2. Selection process. Firstly, to propagate from time step $k-1$ to k, the sigma points are specified. Here, the sigma points are selected and their associated weights are specified as the following equation,

$$\chi_{k-1} = [\hat{x}_{k-1}\, \hat{x}_{k-1} + \eta\sqrt{P_{k-1}}\, \hat{x}_{k-1} - \eta\sqrt{P_{k-1}}]$$
$$k \in \{1, \ldots, \infty\} \tag{15}$$

3.1.1.3. Time updating process. Use the nonlinear system equation $f(\cdot)$ to transform the sigma points into vectors and combine the vectors to obtain a priori state estimate at time k which is given by the following formula

$$\chi_{k/k-1} = g(\chi_{k-1}, u_{k-1}) \tag{16}$$

$$\hat{x}_k^- = \sum_{j=0}^{2n} \gamma_j^{(m)} \chi_{j,k/k-1} \tag{17}$$

Estimate the priori error covariance by adding Q to the end of the equation in order to take the process noise into account

$$P_k^- = \sum_{j=0}^{2n} \gamma_j^{(c)} [\chi_{j,k/k-1} - \hat{x}_k^-][\chi_{j,k/k-1} - \hat{x}_k^-]^t + Q \tag{18}$$

$$Y_{k/k-1} = h(\chi_{k/k-1}) \tag{19}$$

$$\hat{y}_k = \sum_{j=0}^{2n} \gamma_j^{(m)} Y_{j,k/k-1} \tag{20}$$

The time update equations are completed at this point and the measurement update equations need to be implemented in the final part of the UKF algorithm.

3.1.1.4. Updating process for measurement. Choose sigma points with appropriate changes since the current best guess for the mean and covariance of the point is calculated. After that, the nonlinear measurement equations are to be transformed the sigma points. Combine the Y_k vectors to obtain the predicted measurement at time k. Then estimate the covariance of the predicted measurement by adding L_k to the end of the equation in order to take the measurement noise.

$$P_{y_k,y_k} = \sum_{j=0}^{2n} \gamma_j^{(c)} [Y_{j,k/k-1} - \hat{y}_k][Y_{j,k/k-1} - \hat{y}_k]^t + F \tag{21}$$

Estimate the cross covariance between x_k, y_k

$$P_{x_k,y_k} = \sum_{j=0}^{2n} \gamma_j^{(c)} [\chi_{j,k/k-1} - \hat{x}_k^-][Y_{j,k/k-1} - \hat{y}_k]^t \tag{22}$$

Finally, the measurement update of the state estimate can be performed by the normal Kalman Filter equations,

$$M_k = P_{x_k}, y_k P_{y_k}^{-1}, y_k \tag{23}$$

$$\hat{x}_k = \hat{x}_k^- + M(y_k - \hat{y}_k) \tag{24}$$

$$P_k = P_k^- - M_k P_{y_k,y_k} L_k^t \tag{25}$$

where Q is the process noise covariance. Then compute the filter gain K_k, the state mean m_k and the covariance P_k, conditional to the measurement y_k. This is processed by UKF model for estimating the state variables. From the state vari-

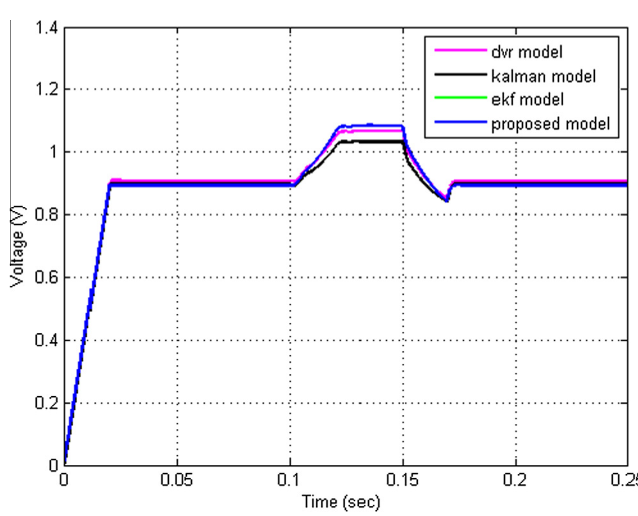

Figure 10 Comparison performance of positive sequence amplitude for all controllers during fault.

ables, symmetrical components are determined. It is given as follows:

$$\left.\begin{aligned} V_{0m} &= \sqrt{x_1^2+x_2^2};\ \phi_0 = \tan^{-1}\left(\tfrac{x_2}{x_1}\right) \\ V_{pm} &= \sqrt{x_3^2+x_4^2};\ \phi_p = \tan^{-1}\left(\tfrac{x_4}{x_3}\right) \\ V_{nm} &= \sqrt{x_5^2+x_6^2};\ \phi_n = \tan^{-1}\left(\tfrac{x_6}{x_5}\right) \end{aligned}\right\} \quad (26)$$

From Eq. (26), symmetrical components are determined and utilized by proposed control module will generate the proper control signals to the PWM of VSI. Now, the proposed control scheme after the estimation of symmetrical components is detailed in following subsection.

The UKF estimation is illustrated in Fig. 2.

From Fig. 3, it utters that, system supply voltages are calculated and fed to UKF model. This UKF model inspects supply voltages and estimates the symmetrical components. Next for recognizing the swell occurrence the amplitude of the positive sequence component is examined. The swell appearance is identified by making sure the difference between estimated positive sequence and its nominal value. It indicates the swell detection if the declared voltage increases above predefined thresholds is known as swell detection. Sample and hold blocks are motivated with the finding of swell appearance from memory module to present reference signals.

Currently, compensation is performed with swell voltages i.e., the reimbursement makes the system voltages go back to the swell condition where swell is not there. The function of

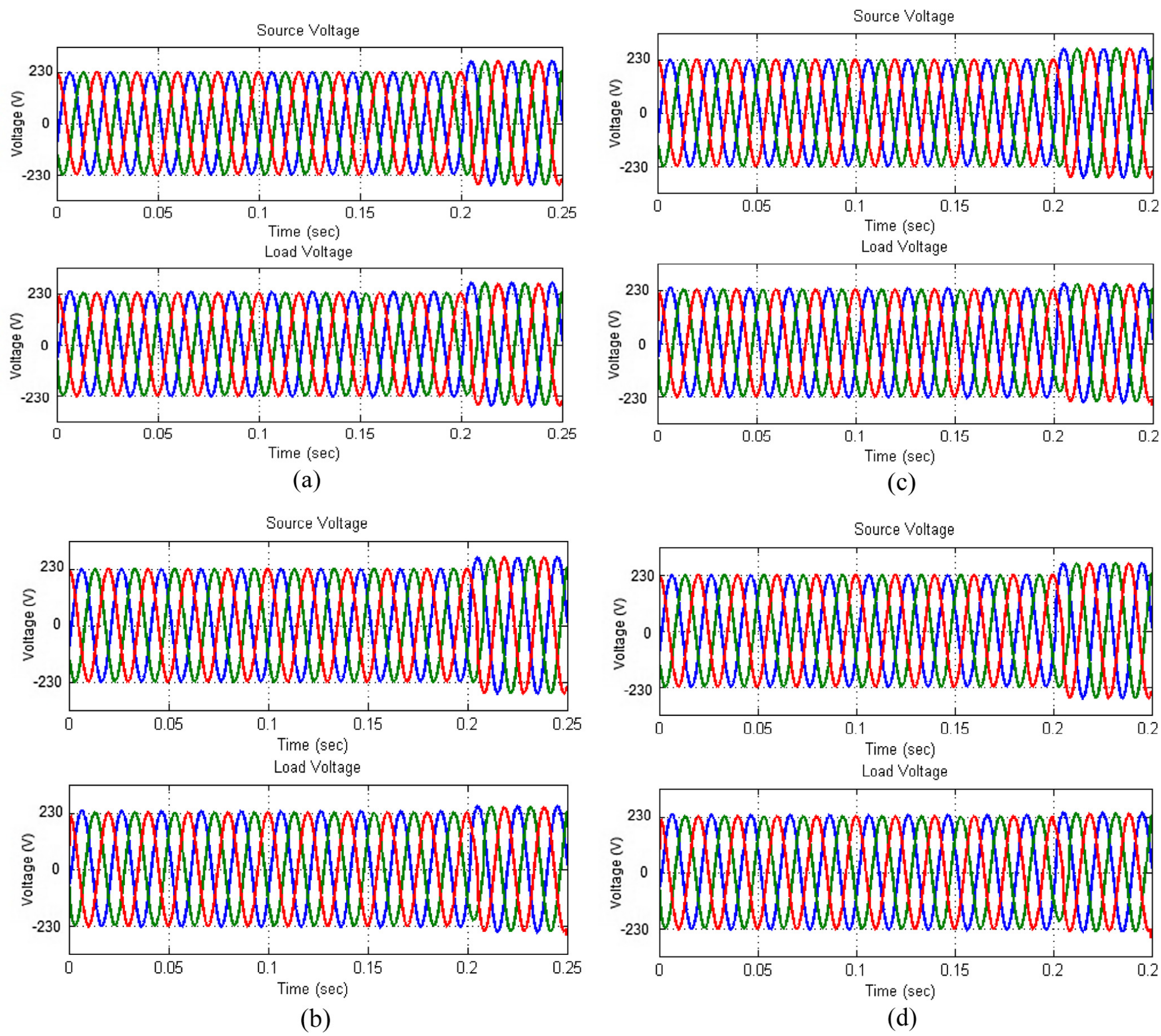

Figure 11 (a) Source and load voltage performance of conventional controller during voltage swell condition; (b) source and load voltage performance of KF based DVR controller during voltage swell condition; (c) source and load voltage performance of EKF based DVR controller during voltage swell condition; (d) source and load voltage performance of proposed controller during voltage swell condition.

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swell voltage and computing eradicating voltage for negative sequence component is also similar as positive sequence component. Both are included to present the injecting voltage once the compensation and removal voltages are worked out. This injecting voltage will repay the voltage swell occurred at load bus. Then the analysis of the proposed hybrid method is described in the following section.

4. Results and discussion

In this paper, a UKF based DVR is proposed for mitigating the voltage swell in distribution system. The proposed method is implemented in MATLAB/Simulink working platform. Here, the estimation method is based on UKF which is helping the control algorithm for producing reference signals of VSC of DVR. With this estimation technique, voltage swell issues are found out with precision and faster performance to revoke out the swell appearance in sensitivity load connected distribution systems. Then the controlled signals are generated from the proposed technique which can generate the controlling pulses for improving the performance of DVR. The Simulink model of the proposed system is illustrated in Fig. 4. The implementation parameters are represented in Table 1. The performance analysis of the proposed method is determined and described in the following section.

4.1. Evaluation of performance analysis

In this section, the performance of the proposed controller is analyzed. The performance of the proposed method is evaluated during the fault condition and their results are analyzed in a different stage which is described as follows:

(a) Voltage Swells in the beginning stage.
(b) Voltage Swells in the middle stage.
(c) Voltage Swells in the ending stage.

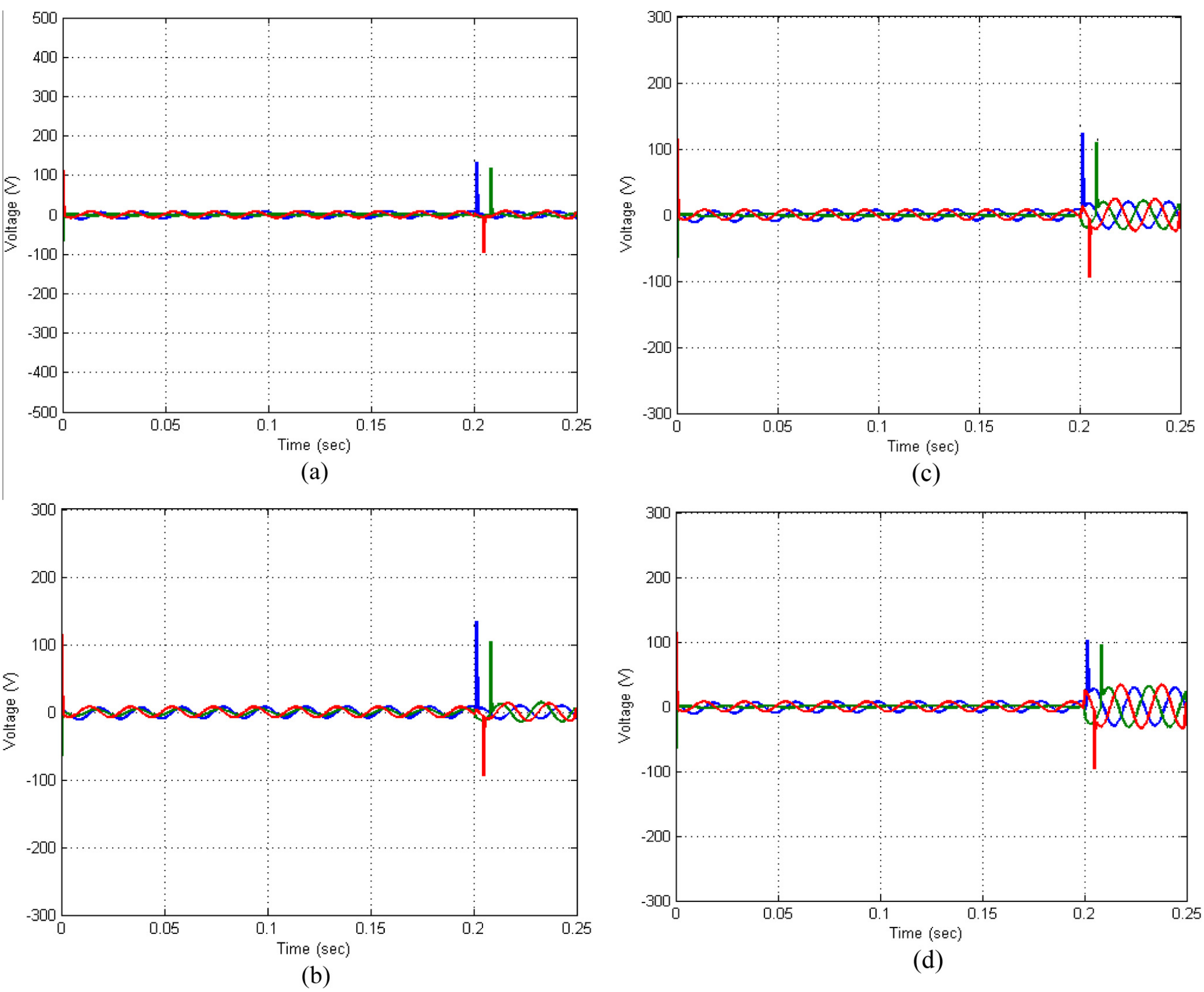

Figure 12 (a) Performance of injected voltage using conventional controller during fault; (b) injected voltage performance of LKF based DVR controller during fault; (c) injected voltage performance of EKF based DVR controller during fault; (d) injected voltage performance of UKF based DVR controller during fault.

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The analyzed outputs of the proposed method are compared with DVR controller and EKF based DVR controller.

(a) *Voltage Swells in the beginning stage*

In this section, the voltage swell is analyzed in the beginning stage. The simulation started with the supply voltage swell is generated as shown in Fig. 5(a). As observed from this figure the amplitude of supply voltage is increased about 25% from its nominal voltage and the voltage swell is not reduced properly. Because, it depends on the DVR working performance, if the DVR is not working properly, then the voltage swell is not compensated properly. Therefore, an estimation method based DVR is used to compensate the voltage swell. By using EKF based DVR controller, the voltage swell is compensated and their performance is illustrated in Fig. 5(c). Before that, the injected and the load voltages are illustrated in Figs. 5 and 6 respectively. Also, the EKF based DVR controller injected voltage performances are examined and contrasted with the proposed controller. From the assessments, it states that, proposed controller has excellent estimation than EKF basis controller and conventional controller.

(b) *Voltage Swells in the middle stage*

In Fig. 8, during starting time of the simulation the supply voltage with swell and related load voltage due to the conventional controller is advertised. From Fig. 7, it expresses, the supply voltage has around 25% expanded in it because of the fault event and as the actual employed supply voltage is 230 V. The injected voltage that is produced by DVR in order to correct the load voltages and the load voltages maintained at the constant are shown in Fig. 9(a)–(d), respectively (see Fig. 10).

(c) **Voltage Swells in the ending stage**

In this section, the simulation started with the supply voltage swell is generated as shown in Fig. 11(a). In Figs. 11–13 the respective injected voltages by proposed controller are offered.

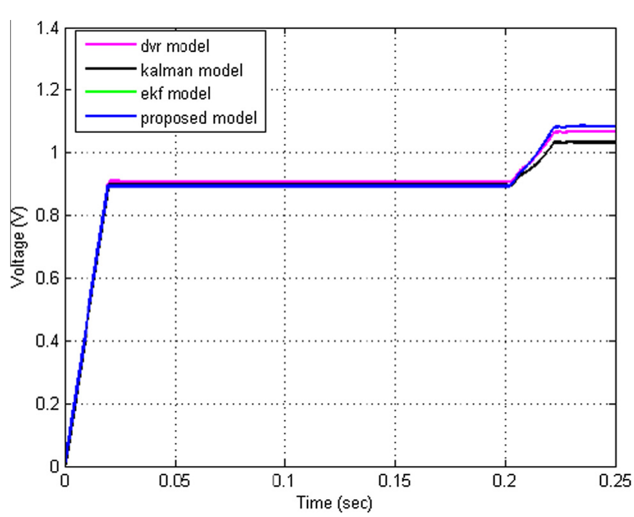

Figure 13 Performance of positive sequence voltage using various controllers during fault.

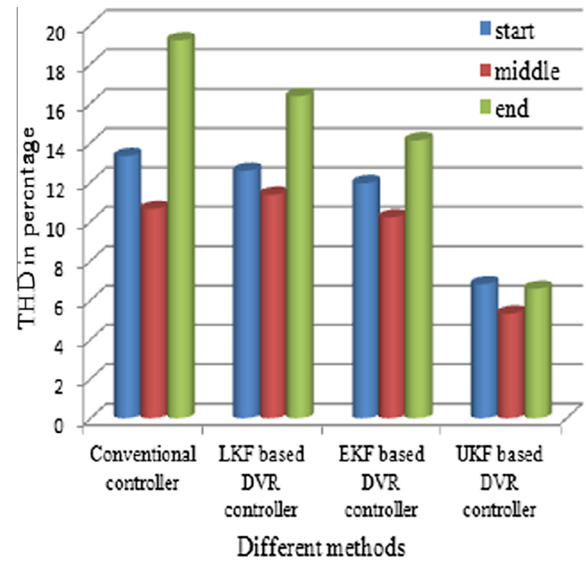

Figure 14 Performance analysis of THD in different stage.

Table 2 THD values for different controller.

Methods	THD values		
	Starting stage	Middle stage	Ending stage
Conventional controller	13.33	10.64	19.21
LKF based DVR controller	12.58	11.36	16.37
EKF based DVR controller	11.95	10.21	14.13
UKF based DVR controller	6.82	5.32	6.58

This is the desired voltage better than conventional controller and EKF basis controller for any sensitive load.

4.2. *Performance analysis of THD*

By the FFT analysis, following table shows the total harmonic distortion with conventional controller during swell condition and Fig. 14 shows THD elimination with proposed controller (see Table 2).

From the above considerations, the proposed controller achieves better performance for compensating the voltage swell problem with the help of UKF estimation methods. The harmonic voltage and the DC voltages are almost maintained to the reference value under all conditions. From this estimation comparisons and injection voltage comparisons, it is done that the proposed controller based on UKF model has better performance than conventional and EKF basis controller for swell compensation.

5. Conclusion

The modeling and simulation of a DVR utilizing MATLAB/Simulink have been presented. A control system based on the estimation technique which is a UKF based the DVR and its reference for swell correction has been presented. The performance of the proposed controller was compared with the conventional controller and EKF based DVR controller. From the comparison results, the UKF based DVR handles both balanced and unbalanced situations without any difficulties and injects 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. Therefore, the proposed controller has enhanced performance in compensating load voltage and estimating symmetrical components.

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