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Fast detection technique for voltage unbalance in three-phase power system

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ABSTRACT

In this paper, the problem of voltage unbalance in the three-phase power systems is examined. A fast detection technique (FDT) is proposed to detect the voltage unbalance precisely and speedily. The well-known detection methods require more than one cycle time to detect the unbalanced voltages, whereas the proposed technique detects the unbalanced situations speedily in a discrete manner. Reducing the time duration required to detect the unbalanced voltages will enhance the dynamic response of the control system used to balance these voltages. The FDT acquires the instantaneous values of the three load voltages, calculates the sum and the space vector for these voltages at each sample, and utilizes these parameters to detect the voltage unbalance accurately within a quarter of the cycle time. A proof-of-concept simulation model for a real power system has been built. The parameters of the aqaba-qatrana-south amman (AQSA) Jordanian power system are considered in the simulation model. Also, several test cases have been conducted to test and validate the capabilities of the proposed technique.

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1. INTRODUCTION

The three-phase power systems suffer from different challenging problems, e.g., unbalanced voltages at the load side [1]-[3]. The voltage unbalance usually degrades the power quality of the electrical system [4], [5]. As a result, the U.S. economy loses between 15 to 24 billion dollars a year in power quality problems [6]. In modern buildings, the frequent use of photovoltaics (PVs), battery storages, and charging stations for electric vehicles (EV) intensify the voltage unbalance problem [4], [7]. Additionally, the malfunctions of the electrical equipment in the power distribution systems normally lead to unbalanced voltages [8]. In general, the voltage unbalance in electrical power systems is resulted from either unbalanced loads or asymmetries in network topology [9]. In most practical cases, the unregulated distribution of loads is the main factor that causes the unbalanced voltages [10]. Subsequently, the volt-amperes of the three lines between the generator and the load become different, and thus generating unbalanced voltages at the load side. Maintaining balanced voltages at the load side is not always possible. This is due to the frequent connection and disconnection of the loads and the uneven load distribution between the three-phases [11]. Therefore, changing the system configuration through the feeder switching operations may balance the electrical power distributions. This operation is based on allocating single-phase loads equally across the three-phase system.

Dissimilar inter-stage coupling of impedances and asymmetrical transformer windings normally lead to network asymmetries [12], [13]. It is challenging to detect the sources that cause voltage unbalance, especially in the power interconnected networks containing untransposed transmission lines and unbalanced loads. Many problems are associated with the voltage unbalance, such as excessive energy losses, heating up the system equipment, and the possibility of system instability [14]-[16]. The effect of the unbalanced voltages appears clearly on three-phase motors [17], [18]. The inversely rotating magnetic field of the negative-sequence system causes a negative braking torque. This torque has to be subtracted from the base torque and thus weakening the machine torque. In addition, the excessive power losses and the heating due to unbalance conditions will reduce the efficiency of the induction motor [19]. The voltage unbalance creates adverse effects on electrical equipment. The efficiency of transformers, cables, or lines is reduced due to the negative sequence components in which the equipment operating limits are determined by the RMS rating current [20]. Additionally, the unbalanced conditions of power converters produce characteristic and uncharacteristic harmonics [9], [21].

Employing the static volt-ampere-reactor compensation (SVC) in the electric power system provides many advantages such as voltage regulation and load balancing, and also enhances the system stability [22]-[24]. To balance three-phase load currents, the SVC needs to absorb a particular amount of positive or negative reactive power to produce zero resultant reactive power at the SVC load common point [25]. However, the unbalance conditions of SVC will generate uncharacteristic harmonics. This will generate more power losses in the power system transmission lines. To reduce the power outage duration, the restoration of faulted lines or load changes should be achieved quickly. Additionally, the dynamic response of the controller used to balance the three-phase voltages needs to be enhanced by reducing the time duration required to detect the unbalanced voltages. In this work, the three load voltages are acquired intermittently to determine the voltage unbalance speedily. The detection of voltage unbalance is based on calculating the sum (V_{sum}) and the space vector (V_{space}) of the three load voltages at each sample. The V_{sum} and V_{space} parameters are utilized by a novel algorithm to detect the voltage unbalance quickly and precisely.

The paper is organized as follows: Section 2 represents a literature review of similar work. Section 3 introduces the three-phase unbalance electric power system. The discrete data measurements are discussed in sections 4 and 5. The proposed fast detection technique (FDT) is introduced in section 6. Section 7 represents the effect of unbalanced load changes and unsymmetrical power system faults on the three load voltages, together with the simulated results. Finally, conclusions are introduced in section 8.

2. LITERATURE REVIEW

To study the unbalance voltage in a three-phase electrical power system, the so-called Fortescue components or symmetrical components are employed [26]. In this method, the three-phase system is decomposed into positive-sequence, negative-sequence, and zero-sequence subsystems. The voltage unbalance is defined by National Electrical Manufacturers Association (NEMA) as maximum deviation from the average of three-line voltages, referred to the average of three-line voltages [14], [27] Furthermore, it is defined in IEEE Std.936-1987 as the difference between the highest and the lowest RMS voltages, referred to the average RMS of the three voltages [28]. The IEEE Std.1159-1195 provides the confirmed true definition, which is the ratio between the negative-sequence and the positive-sequence voltages [29]. It is recommended that the voltage unbalance for AC motors do not exceed 1% [14]. If a motor with 94.4% efficiency, 1800 RPM, and 100 hp is operating at 2.5% unbalance conditions, the motor efficiency will reduce to 93% [14].

The space vector (SV) converts the effect of the three instantaneous values for the three-phase quantities into a rotating two-axis complex plane [30], [31]. This property of the SV is employed in the three-phase systems to convert the analysis into a stationary state of α-β axis. This will simplify the analysis of the three-phase electric power system. A space vector modulation method is employed in three-phase inverters to improve the inverter's output by generating fewer harmonics [24], [32], [33]. Furthermore, the space vector was used in the author's prior work for voltage regulation [34].

Many research efforts have been directed toward detecting and solving the voltage unbalance problems in the three-phase electrical network. Paranavithana and Perera [12] assigned the location of individual lines causing voltage unbalance, by determining the line coupling impedance between the positive and negative sequence networks. Sun *et al*. O'Rouke *et.al*, [35], [36] developed an algorithm for voltage unbalance detection based on Clark transformation. In this algorithm, the three voltages are converted to α–β stationary system. However, by using this method, the voltage unbalance can be detected after a complete cycle time, which is 20 milliseconds in a 50 Hz power system. The unbalanced three-phase supply voltages may exist in the power distribution system. The calculation of the voltage unbalance factor (VUF) was obtained through the transformation of voltage phasors in a three-phase power system into simple trigonometric equations [37]. This method reduced the number of parameters used in the calculation process, leading to fewer clock cycles for VUF calculation. Chen *et al*. [38], the VUF is defined as the ratio of negative sequence to positive sequence voltages. The time needed to calculate the negative and positive sequence voltages is one cycle time. Additional half-cycle time is needed to calculate the VUF. Consequently, by using this method, voltage unbalance can be detected after one and a half cycle time which is 30 milliseconds in a 50 Hz power system.

Shigenobu *et al*. [39] suggested a developed mathematical approach to detect the voltage unbalance precisely in different conditions. In this approach, an additional VUF is calculated based on the zero-sequence voltage in the symmetrical component method. Accordingly, by using this method, voltage unbalance can be detected after one and a half cycle time. Girigoudar *et al*. [40] suggested using three metrics to detect the unbalance voltages accurately in power systems, namely, VUF, phase-voltage unbalance rate (PVUR), and line-voltage unbalance rate (LVUR). Although this method will minimize the effect of unbalance voltages according to different metrics, it needs a relatively higher exciting time (i.e., more than one and a half cycle time). Ghijselen *et al.* [41], the percentage of VUF is determined directly from the three RMS line voltages. The triangle of three unequal voltages is divided into two equilateral triangles, in which the triangle side lengths are the positive and negative sequence voltages. Therefore, a complete cycle is needed to calculate the voltage unbalance using this definition. Sawitri *et al.* [42] Okelola *et al.* [43] applied the support vector machine (SVM) and neural network (NN) respectively to detect the voltage unbalance in induction motors. Additionally, Alkayyati *et al*. [44], [45] employed optimization with machine learning techniques to solve the unbalance problem in electrical power systems.

3. THREE-PHASE UNBALANCE SYSTEM

The three-phase power systems are ideally balanced, and the related distribution systems are designed carefully to guaranty the overall balance in the three phases. For any balanced electric power system, the three voltages are equal in magnitude and out-of-phase by 2π/3 rad. It is important to keep the system voltage within specific limits at different points throughout the power system. Different kinds of large disturbances (e.g., transmission line faults and sudden load changes) normally distort the performance of the electrical power system, such as the voltage balance. In other words, unsymmetrical faults in the transmission lines or unbalanced load changes will directly affect the balance of the three-phase system and produce unbalanced currents and voltages. Consequently, three components will be generated, namely, zero-sequence, positive-sequence, and negative-sequence components ($\vec{V}_0, \vec{V}_1, \vec{V}_2$). By considering the operator (a), each one of the three unbalanced voltages ($\vec{V}_a, \vec{V}_b, \vec{V}_c$) can be written in terms of the three sequence components ($\vec{V}_0$, $\vec{V}_1$, $\vec{V}_2$) as shown in (1) [46].

$$\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix}\begin{bmatrix}\vec{V}_0\\ \vec{V}_1\\ \vec{V}_2\end{bmatrix} = A\begin{bmatrix}\vec{V}_0\\ \vec{V}_1\\ \vec{V}_2\end{bmatrix} \quad (1)$$

Where the rotation operator a is given by: $a = e^{j\frac{2\pi}{3}}$, The inverse of the matrix (A) is given by:

$$A^{-1} = \frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}$$

Multiplying (1) by (A^{-1}) gives the three sequence components as shown in (2).

$$\begin{bmatrix}\vec{V}_0\\ \vec{V}_1\\ \vec{V}_2\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}\vec{V}_a\\ \vec{V}_b\\ \vec{V}_c\end{bmatrix} \quad (2)$$

In this work, both the sum and the space vector of the three voltages are calculated at each sample and utilized to detect the voltage unbalance quickly. The zero-sum of the three instantaneous voltages is not a clear indication of voltage balance. Hence, the calculation of space vector is required to ensure precise detection of unbalanced voltages. The space vector ($\vec{V}_{\text{space}}$) depends on the three instantaneous voltages and can be calculated as shown in (3) [46]. For balanced conditions, the magnitude of the space vector is fixed at any instant of time.

$$\vec{V}_{\text{space}} = \text{a}^0 v_{a(t)} + \text{a}^1 v_{b(t)} + \text{a}^2 v_{c(t)} \quad (3)$$

4. DISCRETE DATA MEASUREMENT

In this work, measurements of discrete data are employed to acquire different variables of the AQSA Jordanian electrical power system at a discrete-time, i.e., samples f (kT_s), where T_s is the sampling period and k is an integer with the range $1 \leq k \leq 20$. The three load voltages are measured at the sample. Besides, the space vector value and the sum of these voltages should be calculated to detect the voltage unbalance quickly and precisely. The number of samples per cycle (ns) is given by (4).

$$ns = \frac{T}{T_s} \quad (4)$$

Where:
- T is the cycle time, which equals 0.02 sec in 50 Hz power system.
- Ts is the sampling period, which equals 1 ms for 20 samples/cycle in 50 Hz power system.

In general, the balanced three-phase variables v_a, v_b, and v_c produce zero-sum at any instant of time. The space vector for each of the three voltages v_a, v_b, and v_c is the corresponding variable on its axis at the a-axis of operator a^0, b-axis of operator a^1, and c-axis of operator a^2. The total value of the space vector in a balanced condition is fixed at all instants of time. The properties of the space vector and the sum of the three voltages are used in this work to determine the voltage unbalance in a very short time.

5. THE SUM OF THE THREE INSTANTANEOUS LOAD VOLTAGES

The sum of any three balanced voltages is zero. For the three-phase power system shown in Figure 1, the three-phase load voltages are given by (5).

$$\begin{aligned} \vec{V}_{\text{abL}} &= \vec{V}_{\text{AB}} - \vec{I}_a.Z_{\text{TTa}} + \vec{I}_b.Z_{\text{TTb}} \\ \vec{V}_{\text{bcL}} &= \vec{V}_{\text{BC}} - \vec{I}_b.Z_{\text{TTb}} + \vec{I}_c.Z_{\text{TTc}} \\ \vec{V}_{\text{caL}} &= \vec{V}_{\text{CA}} - \vec{I}_c.Z_{\text{TTc}} + \vec{I}_a.Z_{\text{TTa}} \end{aligned} \quad (5)$$

Where:
- $\vec{V}_{\text{abL}}, \vec{V}_{\text{bcL}}, \vec{V}_{\text{caL}}$: Load voltages.
- $\vec{V}_{\text{AB}}, \vec{V}_{\text{BC}}, \vec{V}_{\text{CA}}$: Balanced source voltages.
- $Z_{\text{TTa}}, Z_{\text{TTb}}, Z_{\text{TTc}}$: Transmission line and transformer impedances of phases a, b, and c

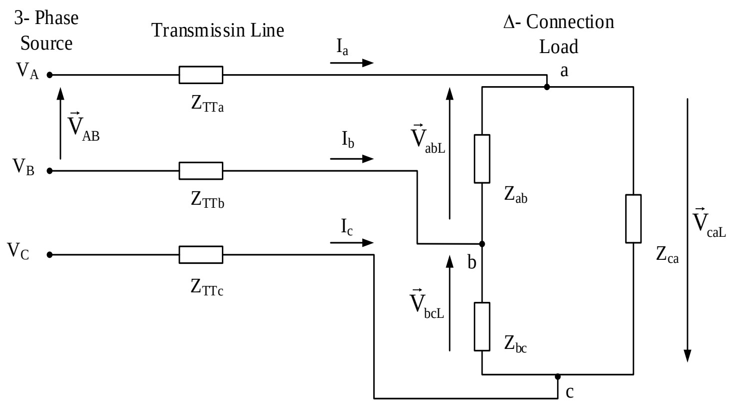


Figure 1. Three-phase power system

In this work, the sum of the three instantaneous load voltages (V_{sum}) is calculated for different cases of load changes (i.e., balanced and unbalanced load changes). The results are simulated for a signal frequency of 50 Hz and 21 samples per cycle. The load changes are applied at the instant t = 0.05 sec (i.e., at the sample number 50). Figure 2 (a) shows the response of the load currents caused by a balanced change in the three-phase loads. This change caused a variation of 24.2% of the average inductive load current. The response of the three load voltages and the sum of their instantaneous values at different samples are shown in Figures 2 (b) and (c) respectively. Figure 3 (a) shows the response of the load currents caused by an unbalanced change in the three-phase load. This change caused a variation of 38.6% of the average inductive load current. The three load voltages and the sum of their instantaneous values at different samples are shown in Figures 3 (b) and 3 (c) respectively. Zero-sum of the three load voltages is obtained for both balanced and unbalanced load changes as shown in Figures 2 (c) and 3 (c). Figure 4 (a) shows the load currents caused by an unbalanced fault in the power system impedance, causing an average variation of 14.3% in load current. The response of the three load voltages is shown in Figure 4 (b). The instantaneous sum of three load voltages is not always zero (i.e., varies with time) as shown in Figure 4 (c). It has a sinusoidal form.

According to the results shown in Figures 2 (c), 3 (c), and 4 (c), two different cases are discussed as follows:

- Case (1): The balanced and unbalanced changes in the three-phase load produce three-line currents. By substituting these currents in (5), the sum of the three instantaneous load voltages V_{sum} is always equal to zero as shown in (6). It is concluded that the balanced and unbalanced changes in the three-phase load, without changing the impedance of the power system (Z_{TT}), will always produce zero-sum of the three load voltages, as shown in Figures 2 (c) and 3 (c)

$$v_{abL(t)} + v_{bcL(t)} + v_{caL(t)} = 0 \quad (6)$$

- Case (2): If there is a change in the impedance (Z_{TT}) of the power system, e.g., the impedance Z_{TTa} is changed to Z'_{TTa}, the instantaneous load voltage $v_{abL(t)}$ is changed to $v'_{abL(t)}$ and $v_{caL(t)}$ to $v'_{caL(t)}$, leading to (7). It is concluded that the sum of three instantaneous load voltages V_{sum} due to a fault in the power system impedance is not necessarily equal to zero. In this case, V_{sum} has a sinusoidal shape as shown in Figure 4 (c).

$$v'_{abL(t)} + v_{bcL(t)} + v'_{caL(t)} \neq v_{abL(t)} + v_{bcL(t)} + v_{caL(t)} \quad (7)$$

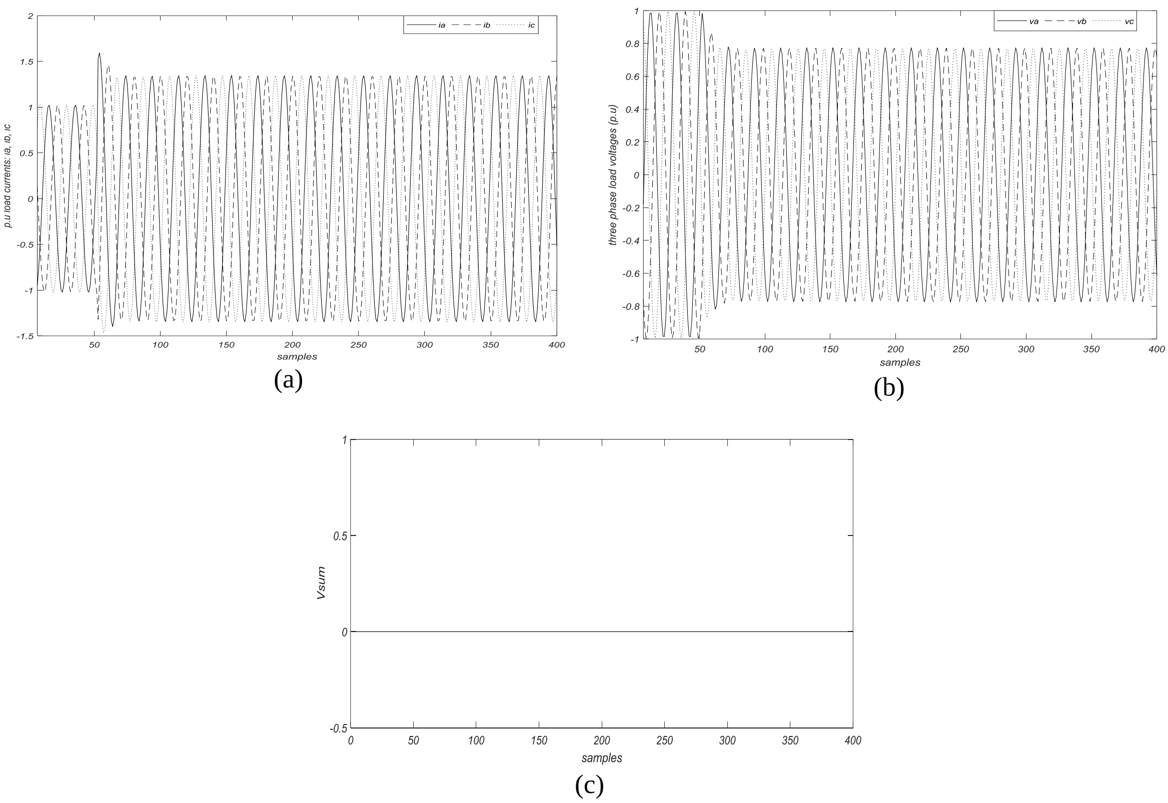


Figure 2. Results for a balanced change in the three-phase load, caused by injection of 24.2% of the average inductive load current, (a) the p.u load currents, (b) the p.u load voltages, (c) the Sum of p.u instantaneous load voltages

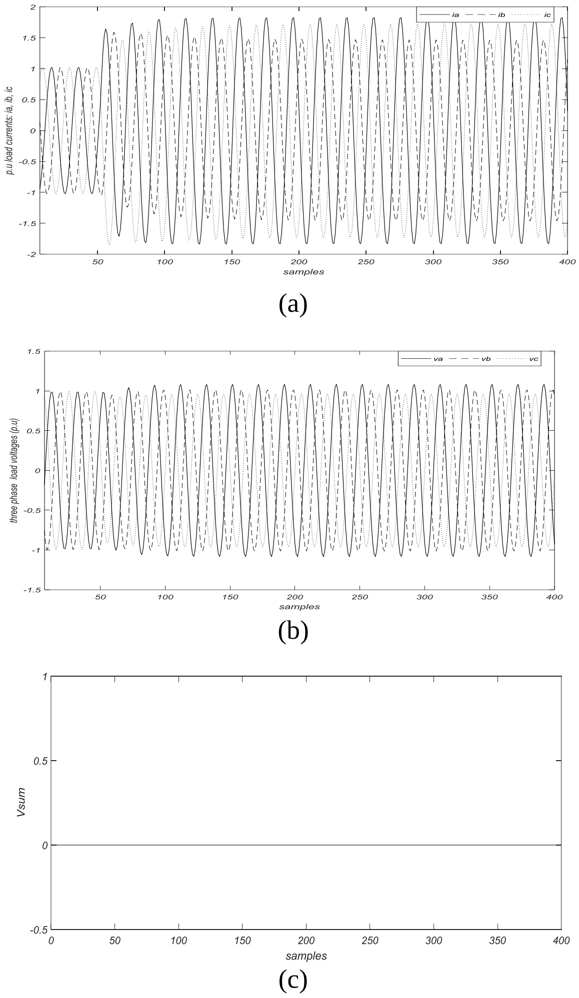


Figure 3. Results for unbalanced change in the three-phase load, caused by rejection of 38.6% of the average inductive load current, (a) the p.u load currents, (b) the p.u load voltages, (c) the sum of p.u instantaneous load voltage

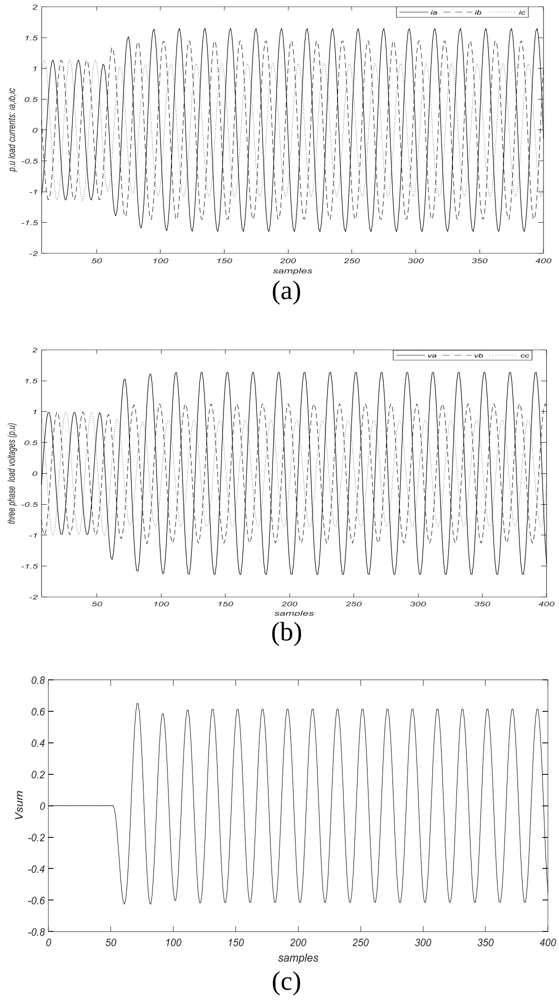


Figure 4. Results for unbalanced fault in power system, causing an average variation of 14.3% in load current, (a) the p.u load currents, (b) the p.u load voltages, (c) the sum of p.u instantaneous load voltages

6. FAST DETECTION TECHNIQUE

A balanced power system produces a balanced voltage throughout the electrical system line. The sum of the three instantaneous voltages is zero at any instant of time. Moreover, the space vector is fixed at these instants of time. In this work, a FDT is developed to detect the voltage unbalance speedily. In the FDT, the cycle time of the 50 Hz system is divided into 21 samples. The space vector (V_{space}) and the sum (V_{sum}) of the three load voltages are calculated at each sample. The proposed technique monitors the behavior of both V_{space} and V_{sum} for 5 consecutive samples and then applies predefined conditions to detect the unbalanced voltages. Consequently, only a quarter of the cycle time is needed to detect the voltage unbalance precisely.

The AQSA Jordanian power system is considered and modeled in this paper as a real case study to validate the proposed technique. Figure 5 shows the one-line diagram of the AQSA power System. South Amman Station is connected to the Aqaba Station through a 328 km transmission line of 400 kV. The 373 MW Qatrana substation lies between South Amman and Aqaba stations. South Amman station distributes about 800 MW through the 400 k V-11 kV multistage transformations to different loads [47]. To guarantee accurate and real system response, the AQSA transmission line is represented in the simulation by three nominal pi-sections. The Aqaba-Qatrana transmission line of 245 km is divided into two pi-sections, while the Qatrana- South Amman transmission line of 83 km is represented by one pi-section. In this work, the authors have developed the FDT to detect the voltage unbalance accurately and in short time. If there is a change in the system, the FDT provides the three following conditions:

- Condition (1): If the calculated sum of the three instantaneous load voltages (V_{sum}) is zero and the calculated space vector (V_{space}) is fixed for the predefined samples, the change is balanced and occurred in the load impedance.
- Condition (2): If the calculated sum of the three instantaneous load voltages (V_{sum}) is zeros and the calculated space vector (V_{space}) is varied in sinusoidal form for the predefined samples, the change is unbalanced and occurred in the load impedance.
- Condition (3): If both the calculated sum of the three instantaneous load voltages (V_{sum}) and the calculated space vector (V_{space}) are varied for the predefined samples, the fault is unbalanced and occurred in the power system equipment. The three conditions are tested and validated using a simulation model in the following section.

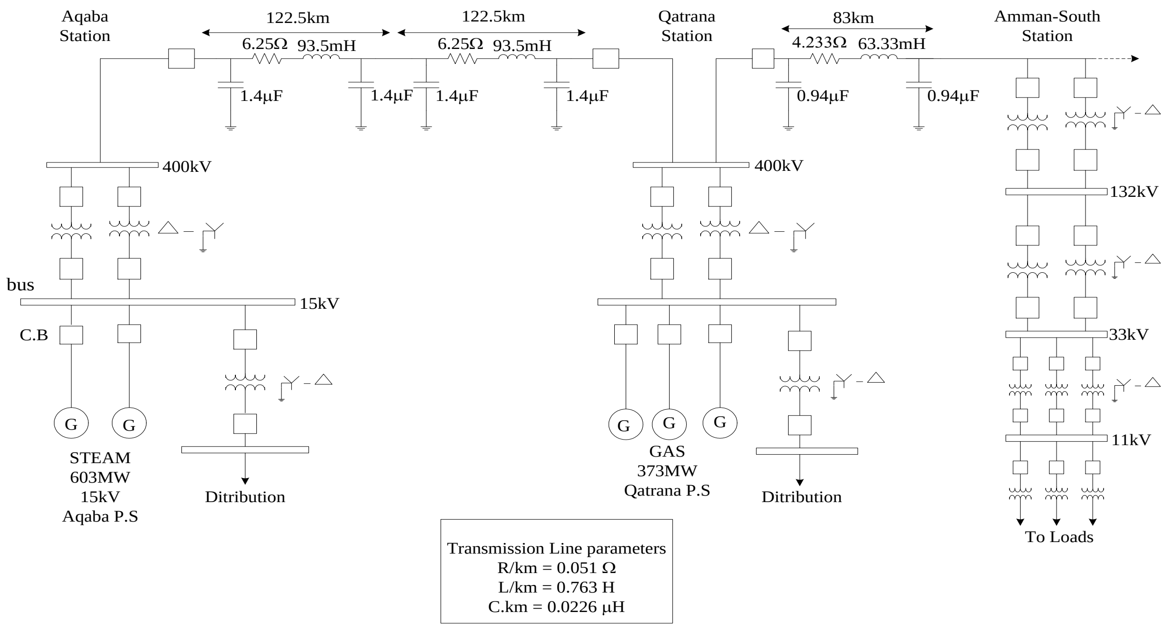


Figure 5. One line diagram of aqaba-qatrana- south amman power system

7. RESULTS AND DISCUSSIONS

In the proposed technique, the sinusoidal signal of the power system is sampled into a predefined number of samples. The sum (V_{sum}) and space vector (V_{space}) of the three load voltages are determined at each sample. The FDT will calculate the V_{sum} and V_{space} instantaneously. According to the three conditions discussed in Section 6, the FDT will detect the voltage unbalance in the system.

Figure 6 shows the simulation model of the AQSA Jordanian electrical power system and the proposed FDT. In this simulation, load changes are applied at the instant t = 0.1 sec (i.e., at the sample number 100). Figure 7 (a) shows the response of the three load voltages due to a balanced change in the three-phase load. This change is caused by injecting 21.4% of the average inductive load current. The V_{sum} and V_{space} for this case are shown in Figures 7 (b) and 7 (c) respectively. It can be observed from Figure 7 that when the balanced change occurred, the V_{sum} was zero at all instants of time and the V_{space} settled at a fixed value. The results in Figure 7 verified Condition (1) introduced in section 6.

Figure 8 (a) shows the three load voltages due to unbalanced change in the three-phase loads. This change is caused by injecting 30% of the average inductive load current. The V_{sum} and V_{space} for this case are shown in Figures 8 (b) and 8 (c) respectively. It can be noted from Figure 8 that when the unbalanced change occurred, V_{sum} was zero at all instants of time, but V_{space} varied in sinusoidal form. The results in Figure 8 verified Condition (2) introduced in Section 6. Figures 9 (a) and 10 (a) show the three load voltages due to unbalanced changes in the power system caused by one line-to-earth and two lines-to-earth faults, respectively. As shown in Figures 9 (b), 9 (c), 10 (b) and 10 (c), both V_{sum} and V_{space} values varied in sinusoidal form. Thus, the results in Figures 9 and 10 verified Condition (3) given in Section 6. A short circuit between the two windings of the 11kV-380V transformer is made and the results of the corresponding three load voltages, V_{sum}, and V_{space} are shown in Figures 11 (a), 11 (b), and 11 (c), respectively. It is also observed that when the change occurred, both V_{sum} and V_{space} varied in sinusoidal form. The results in Figure 11 verified Condition (3) in the proposed FDT as introduced in section 6. According to the results shown in Figures 7-11, it is reasonable to conclude that the proposed FDT can detect the voltage unbalance in the three-phase power system quickly and accurately.

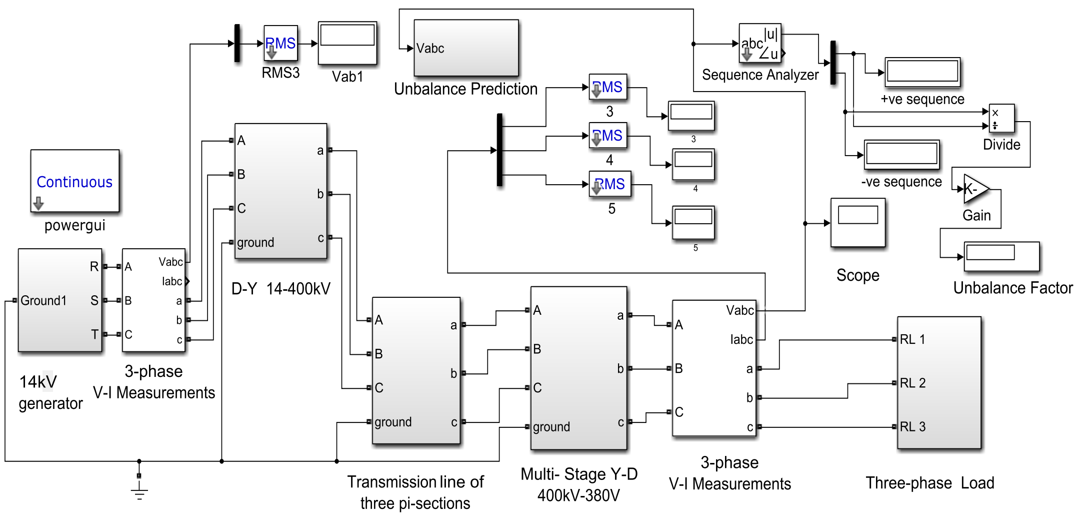


Figure 6. The simulation model of the AQSA electrical power system and the FDT

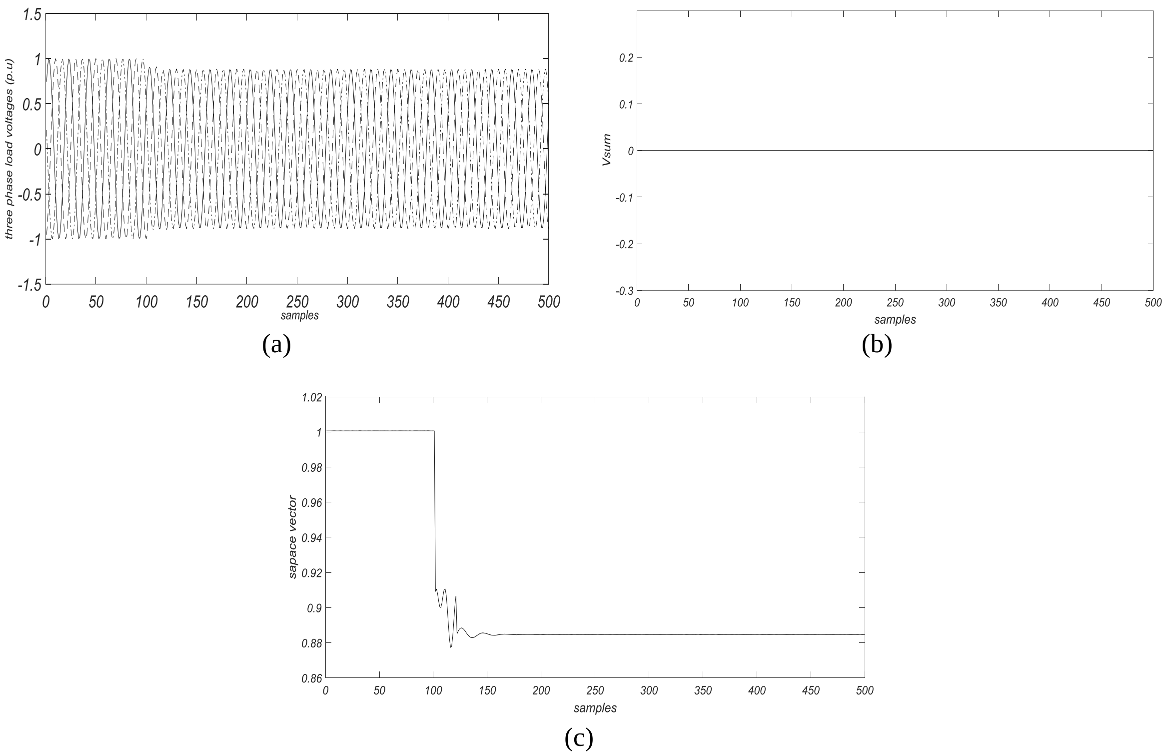
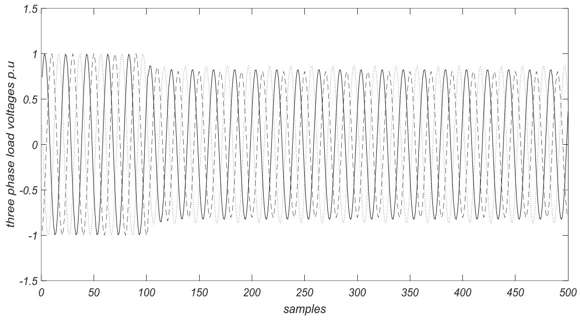
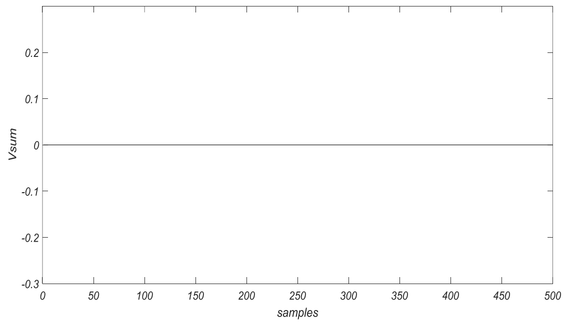


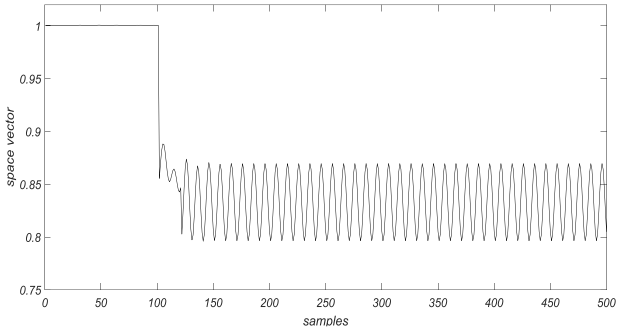
Figure 7. Results for a balanced change in the three-phase, caused by injection of 21.4% of the average inductive load current; (a) the p.u three load voltages, (b) the sum of the three p.u instantaneous load voltages (c) the p.u space vector of the three instantaneous load voltages



(a)

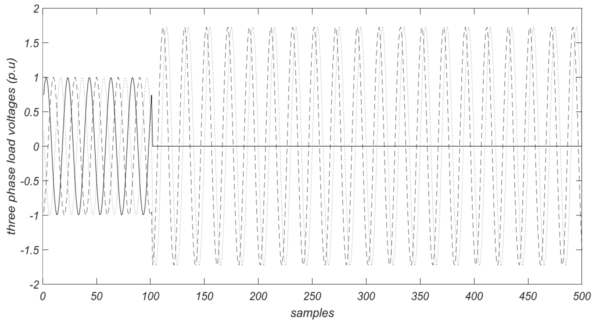


(b)

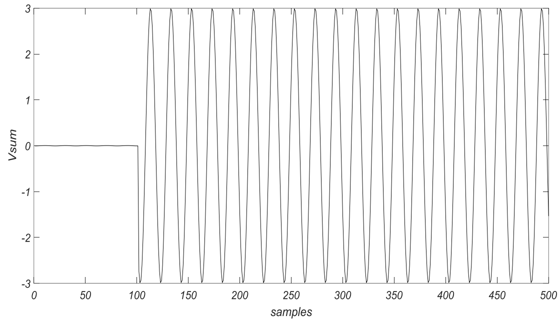


(c)

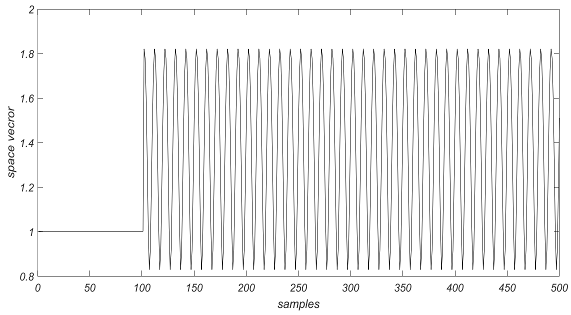
Figure 8. Results for an unbalanced change in the three-phase, caused by injection of 30% of the average inductive load current; (a) the p.u three load voltages, (b) the sum of the three p.u instantaneous load voltages, (c) the p.u space vector of the three instantaneous load voltages



(a)

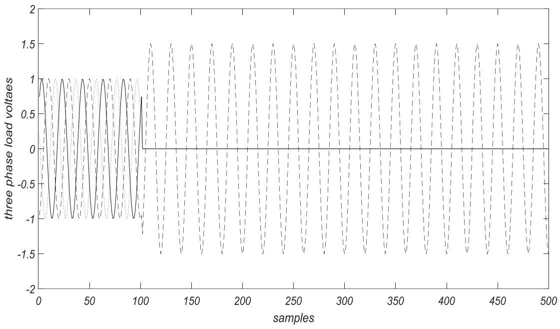


(b)

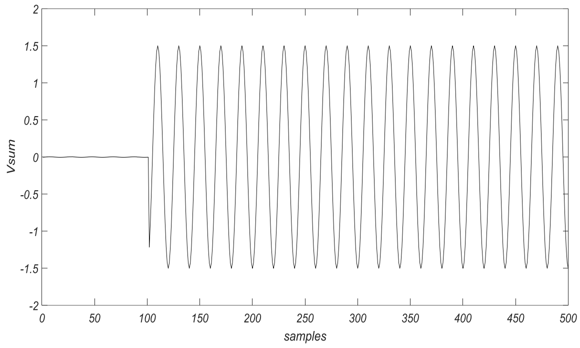


(c)

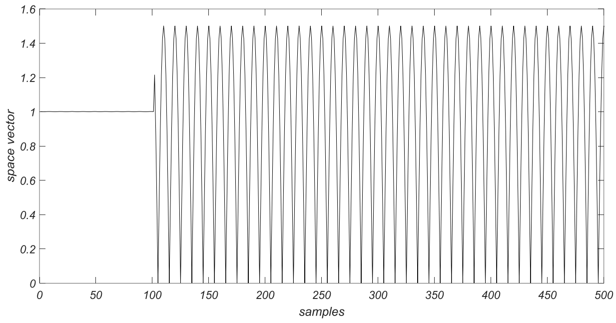
Figure 9. Results for unbalanced fault in the power system, due to one line-to-earth fault; (a) the p.u three load voltages, (b) the sum of the three p.u instantaneous load voltages, (c) the p.u space vector of the three instantaneous load voltages



(a)

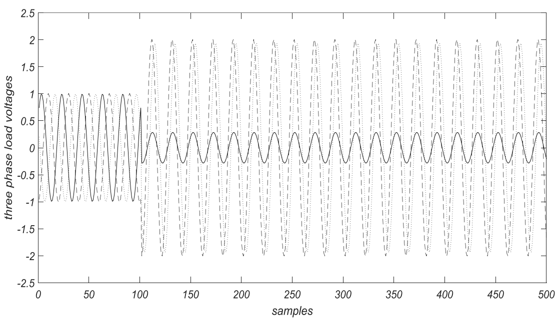


(b)

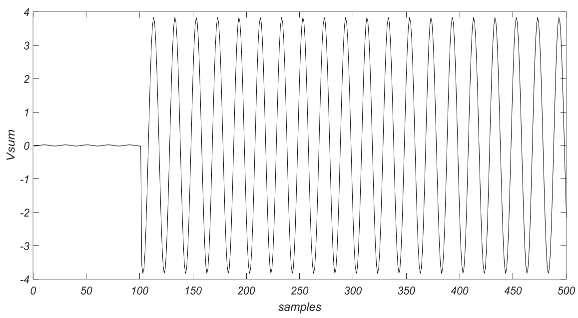


(c)

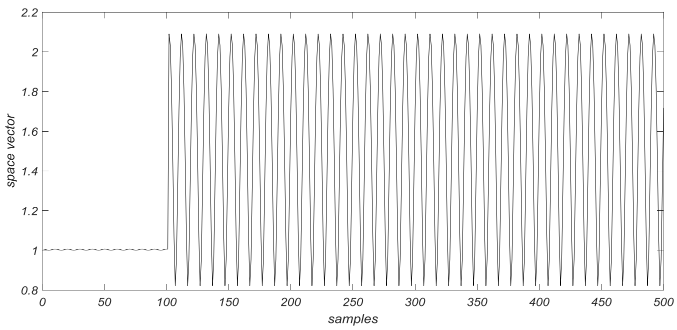
Figure 10. Results for unbalanced fault in the power system, due to two lines-to-earth faults; (a) the p.u three load voltages, (b) the sum of the three p.u instantaneous load voltages, (c) the p.u space vector of the three instantaneous load voltages



(a)



(b)



(c)

Figure 11. Results for unbalanced fault in the power system, due to the short circuit between two windings of the 11kV-380V transformer; (a) the p.u three load voltages, (b) the sum of the three p.u instantaneous load voltages, (c) the sum of the three p.u instantaneous load voltages

8. CONTRIBUTION TO KNOWLEDGE

Table 1 introduces a brief comparison between the detection methods mentioned in the literature and the proposed FDT. Accordingly, the contributions of knowledge in this paper are as follows: i) A novel technique is proposed to detect the voltage unbalance by using the space vector and the sum of the three load voltages. ii) The proposed technique has the superior ability among other techniques in detecting the voltage unbalance quickly within a quarter of the cycle time (5 ms). In other words, the proposed technique minimized the time duration required to detect the unbalanced voltages to 5 ms rather than 20 ms. iii) The proposed technique has the ability to detect the all conditions of voltage unbalance accurately. iv) By reducing the time duration required to detect the unbalanced voltages, the dynamic response of the controller used to balance these voltages is enhanced noticeably.

Table 1. A comparison between different detection methods and the proposed FDT

Research work	The method used for detection	The time needed for data collection (50 Hz Ac power system)	The time needed to detect the voltage unbalance (50 Hz Ac power system)	Comments
[36]	Convert the three voltages to a-b stationary system using Clark-transformation	1 complete cycle (20 ms)	>10 ms	The total time needed for data collection and detecting the voltage unbalance is more than 30 ms
[37]	Transform the voltage phasors into simple trigonometric equations	1 complete cycle (20 ms)	≤10 ms	The total time needed for data collection and detecting the voltage unbalance is less than 30 ms
[38]	Calculate the positive and negative sequence components	1 complete cycle (20 ms)	10 ms	The total time needed for data collection and detecting the voltage unbalance is 30 ms
[39]	Use modified mathematical approach to calculate modified VUF based on zero sequence component	1 complete cycle (20 ms)	10 ms	The total time needed for data collection and detecting the voltage unbalance is 30 ms
[40]	Calculate the VUF, PVUR, and LVUR to detect the voltage unbalance	1 complete cycle (20 ms)	>10 ms	The total time needed for data collection and detecting the voltage unbalance is more than 30 ms
The proposed technique	Calculate the space vector and the sum of three voltages in a discrete manner	4 ms (The time interval between 5 consecutive samples)	1ms	The time needed for collecting data and detecting the voltage unbalance is 5 ms (a quarter of the cycle time)

9. CONCLUSIONS

A novel technique has been proposed to detect the voltage unbalance in the three-phase power system. The proposed FDT depends on measuring the three load voltages in a discrete manner. The FDT utilizes the V_{sum} and V_{space} to detect the unbalanced voltages at the load quickly and precisely. A simulation model for aqaba-qatrana-south amman (AQSA) Jordanian power system has been built and several test cases have been conducted to test and validate the capability of the proposed technique. The results have revealed a high performance of the proposed FDT in detecting the unbalanced voltages quickly within 5 ms.

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