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Design of Central Unit for Voltage Estimation-based Load Shedding Methods to Deal with FIDVR

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ABSTRACT: Fault-induced delayed voltage recovery (FIDVR) occurs after a fault in the network with high penetration of induction motor (IM) loads. Load shedding (LS) is one of the appropriate methods to reduce the destructive effects of FIDVR on the network, and for this reason, the authors have previously presented three LS methods to deal with FIDVR. The first method uses the index of IM loads' power change. The second one is an optimization problem and the third method introduces indicators based on sensitivity analysis. The proposed methods obtain less LS amounts, also, the number of LS locations and moments of proposed methods are fewer than previous ones. However, these methods have different execution times which are related to the speed of the utilized processor; and the suitable method to deal with FIDVR must have the ability to shed the load in the initial moments of this phenomenon. Since the proposed LS methods are centralized, therefore, a central unit is required to monitor the network through the voltage and current sent through PMUs and the status of circuit-breakers, for detecting critical conditions and determining the amount and location of LS. Various states such as estimation of load parameters, detection of fault occurrence and clearance, detection of topology change, and voltage estimation process are also needed before the start of LS calculations, which are discussed in this paper. Also, the telecommunication required by this central unit is provided with a GOOSE message based on IEC 61850 standard.

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1- Introduction

The power network is exposed to new phenomena due to its ever-increasing expansion. With a fault in a network with high penetration of induction motor (IM) loads, the speed of IMs will decrease during the fault. After clearing the fault, it is expected that the voltages will quickly return to their levels before the fault; however, the reactive power required by IM loads increases due to the increase in the ratio of reactance to the resistance of IM loads. The increased demand for reactive power prevents fast voltage recovery, and voltage collapse may even occur. This phenomenon is called fault-induced delayed voltage recovery (FIDVR). There are different methods to control the FIDVR phenomenon, which are categorized into two categories: network and load-side methods. The network side methods try to increase the reactive power generation capability, and the load side ones focus on shedding the loads, respectively.

Some studies have used known power software like PSCAD, InterPSS, etc. to investigate the influence of the distribution network on the transmission network, and the occurrence of the FIDVR phenomenon. A framework has been presented in [1], for performing the dynamic load flow, by which the influence of the distribution network on the transmission network can be studied. Ref. [2] has also presented a simulation framework based on the combination of electromagnetic transient and transient stability to study the FIDVR phenomenon. If a part of the real data that could be used for FIDVR analysis had been missed, ref. [3] has used time-series load flow to estimate the distorted data. A dynamic model for IM based on Lyapunov's pseudo-energy function has been presented in [4], and this model can be considered as a part of the system's dynamic model. By using this model, it is possible to distinguish between different FIDVRs in one bus, in terms of the involved loads and the intensity of FIDVR. An aggregate model for air conditioners (fixed-torque IM) has been presented in [5] which can be used to estimate the percentage of stalled IMs during the occurrence of FIDVR.

An index has been presented in [6] based on the amount of load and short-circuit level of each bus to determine the buses prone to FIDVR. The entropy of the voltage probability density function has been used in [7] to quantify the duration of FIDVR, and the voltage curve that has a lower entropy reaches its final value sooner. Also, the divergence function has been used to compare the final values of voltage curves; so that the divergence value illustrates the lower final value. The effect of ambient temperature has been investigated in [8] on the severity of FIDVR, also, a novel temperature-dependent

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model for IMs has been presented. It has been shown in [9] that in addition to the reactive power supply, the ambient temperature and the rate of use of air conditioners are also affected by the severity of FIDVR. Therefore, a new index based on the aforementioned parameters has been proposed for identifying the most FIDVR-prone buses and electrical areas. An online data mining method has been utilized in [10] for evaluating FIDVR. The voltage instability is checked in the first stage; and if the voltage instability is not detected, the FIDVR detection stage is activated. In this step, the value of the presented index is calculated based on the available voltage data; and then a machine learning algorithm is used to detect the occurrence of FIDVR. The same authors have improved their previous online data mining method in [11] to increase the speed and accuracy of FIDVR detection.

The use of distributed generators [12-16], energy-storage equipment [17], and the installation of a capacitor bank, SVC, and STATCOM [18-22] for injecting reactive power are some of the network-side methods for dealing with FIDVR. Since the power network is a highly nonlinear system, the dynamic models presented to check the stability of the power system are not matched and the assumptions of some models are contradictory to other ones; Therefore, the authors in [23] have used the voltage control scheme independent of dynamic models to control reactive power injection sources to achieve voltage stability during the FIDVR. A large solar farm has been used as STATCOM in [24] to make the reactive power injection method effective. The proposed design has the ability to inject active and reactive power during the day, and reactive power during the night to deal with FIDVR. However, the implementation of network-side methods is costly, and these methods are not suitable for all networks.

The used converter in [25] disconnects the IM from the network and feeds it from an emergency source if FIDVR is detected. However, it cannot be expected that all IM loads act in this way; therefore, load-side methods have been directed towards load shedding (LS). Ref. [26] has presented a local LS scheme that uses an index consisting of active and reactive powers of IM load. Monitoring the imaginary part of admittance seen from the beginning of feeders is the used method in [27] to detect critical FIDVRs. The positive value of the presented index indicates the angular speed recovery of IM loads, and LS will not be required in such conditions. Also, the instability of DGs has been considered as a criterion for LS. Under-voltage load shedding (UVLS) relays are the common protection installed in networks against voltage drops, however, studies have shown that this protection does not have the ability to effectively deal with the FIDVR phenomenon; therefore, researchers have tried to improve this protection. It has been proposed in [28] that UVLS relays should measure voltage changes in addition to monitoring the voltage values. The slope of voltage is compared with the threshold value in this scheme, and if the obtained slope is greater than its threshold, the voltage will return to the critical voltage (V_{crt}) in less time than critical time (t_{crt}) and there will be no need to LS. The authors in [29] have suggested that UVLS relays are equipped with a fuzzy controller to improve their performance during FIDVR. UVLS relays have been improved in [30] so that these relays have the ability to detect the operation of IM loads in their stable or unstable regions by using the relative slip index. If the value of this index is greater than 1 it means that the IM loads are entering the unstable area of their operation, and it is necessary to shed those loads. Under-impedance relay has been updated in [31] for acting as a LS relay to deal with critical FIDVR.

It is also possible to implement the centralized scheme to deal with FIDVR if the studied network is equipped with phasor measurement units (PMU). Considering that LS from one bus also affects the voltage recovery of other buses, therefore, checking all buses at the same time using centralized schemes will have better results than checking the buses separately when using decentralized ones. Several centralized LS methods based on a "faster than real-time" voltage estimation approach have been presented in [32-36]. A central and online LS scheme has been presented in [37] which uses the kinetic energy of IM to determine the effective loads. An evolutionary strategy based on physical laws along with a Markov decision tree is presented in [38] as a voltage control method to deal with critical FIDVRs. This evolutionary strategy which is a data mining method, includes inputs such as voltage and amount of load of each bus, and its outputs are the amount of load that can be shed. The machine learning tool is used in [39] for online LS during the FIDVR. The training data are different states of load and the location and amount of LS corresponding to each state. The trajectory sensitivity analysis method is used to determine the location and amount of LS.

In this paper, the feasibility of implementation of LS methods in [32-34] is investigated. Since the mentioned methods are in wide-area type, their implementation requires the definition of a central unit for processing received data, as well as, telecommunication links to communicate with smart equipment throughout the network. The voltage of buses and the current of loads measured by PMUs are sent to the central unit from these links so that this unit can estimate the parameters of loads at the first stage. Also, these data are used along with the state of the circuit-breakers (CB) to detect the occurrence and clearance of faults and changes in the topology of the network. After determining the current topology of the network, the central unit estimates the voltage of buses for future moments and identifies the buses involved with critical FIDVR. Thus, one of the LS methods presented in [32-34] is used to determine the location and size of LS according to the speed of the processor used in the central unit. Finally, the obtained LS results are applied to the smart switches in the network through communication links. Online control of the network voltage through the proposed LS scheme requires a fast connection, which can be achieved through a special type of communication in the form of a GOOSE message defined in IEC 61850.

2- Design of Central LS unit

It is possible to implement centralized load-shedding schemes to deal with FIDVR if the studied network is

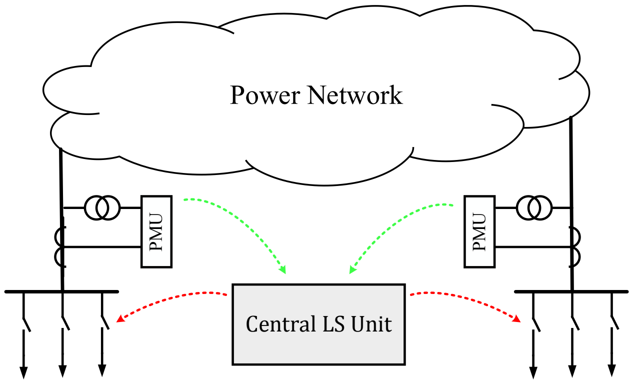

Fig. 1. Communication links of the proposed LS scheme

equipped with PMUs. Considering that shedding the load from one bus also affects the voltage recovery of other buses, simultaneously checking all buses of the network at the same time using centralized scheme will have a better result than checking the buses separately when using decentralized LS schemes; therefore, a wide-area LS scheme based on central unit is presented in this paper which can be seen schematically in Fig. 1.

The measured values of bus voltages and the load currents are sent to the central unit by the PMUs at any moment of time. In normal conditions of network operation, the central unit models the loads fed from each bus in the form of static and dynamic loads using the received information and load parameter estimation methods. If the voltage and current values sent to the central unit by PMUs reveal the occurrence and clearance of fault in the network, the central unit will start to estimate the bus voltages in the next moments using the approach presented in [32-34], and it will send the trip command to the load switches in the network to deal with critical FIDVRs if it's necessary. It is important to mention that the voltage estimation tool used in the central unit only needs 3 consecutive data of voltages and currents after clearance the fault, and there is no need to continuously monitor the network during the occurrence of FIDVR. A detailed explanation about the central unit will be described in the following.

2- 1- Estimation of Load Parameters

The voltage estimation tool presented in [32-34] is a model-based approach containing the three-order model of IM, therefore, the load parameters need to be specified before starting the voltage estimation process. The PMU cannot be widely installed in the distribution network because of its high cost of installation and operation; for this reason, it is assumed that the central unit only receives the data of sub-transmission and transmission buses through PMUs, therefore, this unit will have access to only upstream voltage and current of loads. In such situations, it is recommended to aggregate the loads fed from each bus in the form of hypothetical static load ZIP (constant impedance-current-power) and dynamic loads IMf (fixed-torque IM) and IMv (variable torque IM) according to Fig. 2. This aggregation is applied through the load parameter estimation methods in such a way that the behavior of hypothetical loads matches the behavior of real ones.

The penetration of IM loads is one of the parameters that is calculated through load parameter estimation methods. By conducting initial studies on this coefficient, it is possible to determine under what conditions the network is susceptible to the occurrence of critical FIDVR. By clarifying this point, the unnecessary operation of the proposed LS scheme can be avoided and the time intervals for estimating the load parameters can be considered long. For instance, due to the use of heating equipment in the cold seasons of the year, networks are less exposed to the occurrence of critical FIDVRs; however, this point is not valid in the hot seasons due to the increased use of cooling equipment. The proposed LS scheme should always be ready for operation in the hot seasons of the year, and the time intervals for estimating load parameters should be shorter than in the winter.

2- 2- Detection of Fault Occurrence

Considering that the criterion of the criticality of FIDVR is the voltage remaining in a range lower than the critical voltage when the critical time has passed, therefore, the moment of voltage drop to less than the critical voltage is one of the required parameters of the central unit. Since the momentary voltages of network buses can be monitored by the central unit through the PMUs, therefore, the voltage drop of buses to a value lower than the critical voltage is considered as the moment of fault occurrence with Eq. (1). In the event of a fault, the momentary voltage of some buses will not drop below the V_{crt} due to the large distance from the location of fault, and it is obvious that these buses will not need LS for dealing with the critical FIDVR.

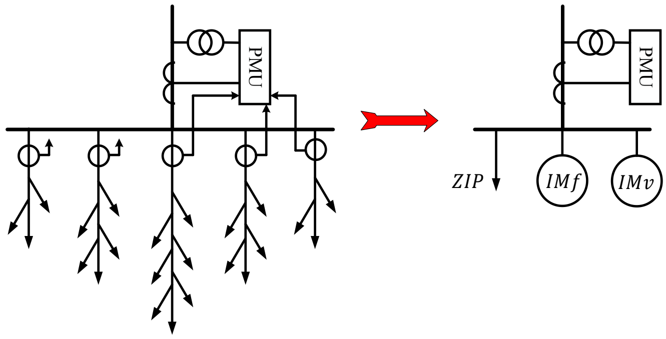

Fig. 2. Replacing all various loads of bus with three hypothetical ZIP, IMf, and IMv loads

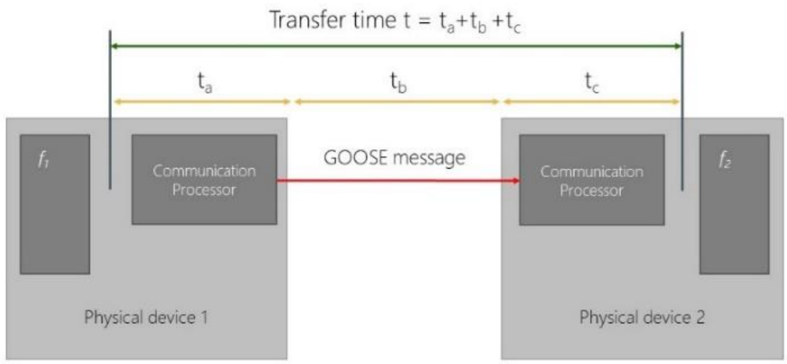

Fig. 3. ducing the time of sending data through the telecommunication link when using the GOOSE message

$$V_{PMU}(t) < V_{crt} \rightarrow t = t_0 \quad (1)$$

2- 3- Detection of Fault Clearance

The proposed LS scheme can start when the fault is cleared from the network, otherwise, the main priority will be fault clearing not Load Shedding. First, the main protection schemes such as distance protection must operate used to clear the fault. In the next step, special protection schemes such as LS will activate to deal with the remaining effects of fault, therefore, there is a need for a method in the central unit to detect the fault clearance. For this purpose, the status information sent by the CBs is used. The central unit detects the occurrence of fault using the data received from the PMUs, and detects the clearance of fault through the analysis of statuses of CBs.

Due to the online functionality of the proposed LS scheme, this scheme requires fast telecommunication connections with the lowest possible delay. The IEC 61850 standard, which is a comprehensive standard in the field of substation automation and design of telecommunications in the power system, provides a feature called GOOSE message to send data quickly. According to the open systems interconnection (OSI) model, each intelligent electronic device (IED) consists of seven layers: physical, data link, network, transport, session, presentation, and application. A message to be sent through telecommunications must pass through these seven layers and a label is added to the original message in each layer. For instance, physical addressing (MAC) is performed at the data link layer, logical addressing (IP) at the network layer, splitting large messages into small packets at the transport layer, etc. it is possible to increase the speed of data sending by skipping some additional packets that layers add to the main message. For instance, there will be no need for queuing as well as logical addressing to send data in such situations; and this new type of data, which is called GOOSE message, can be sent in multicast to the entire system, unlike the conventional data which are exchanged between two IEDs in unicast form. According to Fig. 3, using this type of fast message reduces the time delay in sending data.

If the exchange of data between the central unit and CBs is based on the IEC 61850 standard and using the GOOSE message, the central unit will be aware of the change of status of CBs and topology change in the shortest possible time. According to Fig. 4, sending sampled values by PMU also follows the rules of the GOOSE message. Therefore, all telecommunications required in the proposed LS scheme can

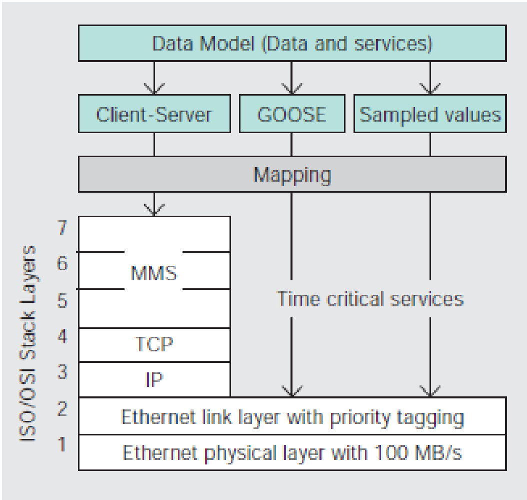

Fig. 4. Intertwining of GOOSE message with layers of OSI model

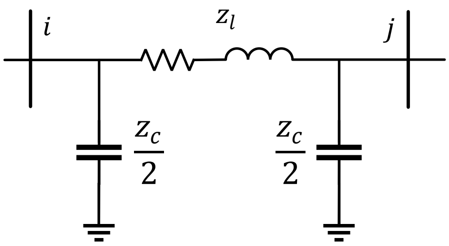

Fig. 5. π model of transmission line

adapt to the GOOSE message, and this point will lead to the achievement of fast telecommunication links.

2- 4- Detection of Topology Change

After clearance the fault, an important point that should be taken into account is the change of network topology due to the disconnection of the faulty line. The elements of network admittance and impedance matrices are used in the voltage estimation process and in the LS methods, therefore, it is necessary to use matrices that conform to the new network conditions. If it is assumed that the line between two buses i and j is out of service, it is enough to change the elements of the admittance matrix between these two buses as Eq. (2). Also, the admittance elements on the main diameter of the matrix should be changed by subtracting the disconnected admittances from the previous values according to Eq. (3). Impedances of one transmission line are available in Fig. 5.

$$\begin{cases} Y_{i,j}^{new} = Y_{i,j}^{old} + \dfrac{1}{z_l} + \dfrac{2}{z_c} \\ Y_{j,i}^{new} = Y_{i,j}^{new} \end{cases} \tag{2}$$

$$\begin{cases} Y_{i,i}^{new} = Y_{i,i}^{old} - \dfrac{1}{z_l} - \dfrac{2}{z_c} \\ Y_{j,j}^{new} = Y_{j,j}^{old} - \dfrac{1}{z_l} - \dfrac{2}{z_c} \end{cases} \tag{3}$$

Inverting the admittance matrix leads to the network impedance matrix, however, this calculation requires lots of time, especially for large networks. To reduce the calculation time, the concept of adding a new line between two existing buses can be used. If a new line with a series impedance z_b is added between two existing buses $i0$ and $j0$, the element of impedance matrix related to the other two buses $i1$ and $j1$ is updated as Eq. (4). The addition of parallel impedance z_b from bus $i0$ to the ground also affects the element of the impedance matrix according to Eq. (5) [40].

$$Z_{i1,j1}^{new} = Z_{i1,j1}^{old} + \frac{\left(Z_{i1,i0}^{old} - Z_{i1,j0}^{old}\right)\left(Z_{i0,j1}^{old} - Z_{j0,j1}^{old}\right)}{Z_{i0,i0}^{old} + Z_{j0,j0}^{old} - 2Z_{i0,j0}^{old} + z_b} \tag{4}$$

$$Z_{i1,j1}^{new} = Z_{i1,j1}^{old} - \frac{Z_{i1,i0}^{old} \times Z_{i0,j1}^{old}}{Z_{i0,i0}^{old} + z_b} \quad (5)$$

The way to update the network impedance matrix for disconnecting the on-service line between buses $i0$ and $j0$ is similar to adding a new branch between those buses, except that the line impedance should be considered negative. If there is a line with impedance z_l between two buses $i0$ and $j0$, adding impedance $-z_l$ between the same buses with the help of Eq. (4) can model the disconnection of that line. In this case, the elements of the impedance matrix are updated based on Eq. (6), and there is no need to reverse the updated admittance matrix of the network. Eq. (7) also shows the way of disconnection of capacitive shunt impedance $z_c/2$ connected to bus $i0$. For this=== purpose, the shunt impedance $-z_c/2$ is paralleled with the existing impedance through Eq. (5).

$$Z_{i1,j1}^{new} = Z_{i1,j1}^{old} + \frac{\left(Z_{i1,i0}^{old} - Z_{i1,j0}^{old}\right)\left(Z_{i0,j1}^{old} - Z_{j0,j1}^{old}\right)}{Z_{i0,i0}^{old} + Z_{j0,j0}^{old} - 2Z_{i0,j0}^{old} - z_l} \quad (6)$$

$$Z_{i1,j1}^{new} = Z_{i1,j1}^{old} - \frac{Z_{i1,i0}^{old} \times Z_{i0,j1}^{old}}{Z_{i0,i0}^{old} - {}^{z_c}/_2} \quad (7)$$

2- 5- Voltage Estimation Process

After receiving the statuses of CBs, the central unit updates the admittance and impedance matrices of the network based on the changes that have occurred. Then, the initial values of IM's state variables including slip and internal voltage are calculated based on the method proposed in [33] and using the previously obtained load parameters by load parameter estimation methods. Determining the network topology, the load parameters, and the initial values of IM's state variables are sufficient to run the voltage estimation process, therefore, the voltage of buses is estimated for the future moments as a "faster than real-time" process with the help of the voltage estimation tool introduced in [32-34]; and it is possible to find out which of the buses have suffered from critical FIDVR. The bus has a critical condition when its voltage does not reach the critical voltage at the critical time after the fault occurrence, because under-voltage (UV) relays may operate in such condition.

2- 6- Load Shedding Methods

By identifying the buses involved with critical FIDVR, LS can be applied to these buses to increase their voltage recovery speed. Since the conditions of the network and loads simultaneously affect the intensity of FIDVR, therefore, the utilized LS methods should be based on the parameters of the network and loads. In the following, three LS methods are proposed to deal with FIDVR. After obtaining the location and amount of load that can be shed and before applying LS to the network, the accuracy of obtained results is checked based on the voltage estimation tool, and if the obtained results do not cause the buses to leave the critical state, the calculations continue in the next iteration.

First Proposed Method [32]: Since the occurrence of the FIDVR phenomenon after the fault clearance is due to the increase in power demand from IM loads, therefore, research on the power changes of IM loads before and after the fault occurrence can provide good vision determine the location of LS. According to Eq. (8), a bus is selected as the location of LS that its' IM loads have the most power changes. The LS steps are considered fixed values in this method; therefore, the implementation of this method requires an initial study to determine the appropriate LS step. If the LS step is chosen to be large, it is possible that non-optimal LS may occur. On the other hand, if the LS step is chosen to be small, the calculation time increases, and the advantage of online LS is lost.

$$loc = \max_{i=1,\ldots,N}\left(\left|S_{M,i}(t_{crt})\right| - \left|S_{M,i}(t_0)\right|\right) \quad (8)$$

Second Proposed Method [33]: If $V = ZI$ is extended based on conditions before and after LS in Eq. (9) and (10), and assuming $I_i^{aLS} = (1 - x_i) I_i^{bLS}$, the voltage after LS depends on the bus voltage and load current before LS, in addition to the amount of LS (variable x) according to Eq. (11). The voltages and currents at before and after LS are indicated by bLS and aLS , respectively.

$$\mathrm{V}^{bLS} = \mathrm{ZI}^{bLS} \rightarrow \begin{bmatrix} V_1^{bLS} \\ \vdots \\ V_N^{bLS} \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1N} \\ \vdots & \vdots & \vdots \\ Z_{N1} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} I_1^{bLS} \\ \vdots \\ I_N^{bLS} \end{bmatrix} \quad (9)$$

$$\mathrm{V}^{aLS} = \mathrm{ZI}^{aLS} \rightarrow \begin{bmatrix} V_1^{aLS} \\ \vdots \\ V_N^{aLS} \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1N} \\ \vdots & \vdots & \vdots \\ Z_{N1} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} I_1^{aLS} \\ \vdots \\ I_N^{aLS} \end{bmatrix} \quad (10)$$

$$\mathrm{V}^{aLS} = \mathrm{ZI}^{bLS} - \mathrm{ZXI}^{bLS} \rightarrow \mathrm{V}^{aLS} = \mathrm{V}^{bLS} - \mathrm{ZXI}^{bLS} \quad (11)$$

An optimization problem can be obtained to determine the location and amount of LS using Eq. (11). The objective function of this optimization problem includes minimizing the amount of LS from each bus according to Eq. (12), and its' constraints guarantee the voltages of buses after LS to be greater than V_{crt} at time t_{crt} . Since the constraint in Eq. (13) is derived from Eq. (11), the amount of LS affects the estimated voltage of the buses after the hypothetical shedding of the load. Since mathematical optimization algorithms have a better ability to achieve the optimal solution than meta-heuristic optimization ones and in less execution time [41-44], this optimization problem is linearized in [33] to be solved with MILP.

$$\min \quad x_1 + \cdots + x_N \tag{12}$$

$$\begin{cases} \left|V_1^{bLS}(t_{crt}) - \left(x_1 Z_{11} I_1^{bLS}(t_{crt}) + \cdots + x_N Z_{1N} I_N^{bLS}(t_{crt})\right)\right| \geq V_{crt} \\ \vdots \\ \left|V_N^{bLS}(t_{crt}) - \left(x_1 Z_{N1} I_1^{bLS}(t_{crt}) + \cdots + x_N Z_{NN} I_N^{bLS}(t_{crt})\right)\right| \geq V_{crt} \end{cases} \tag{13}$$

Third Proposed Method [34]: According to $V^{aLS} - V^{bLS} = Z\left(I^{aLS} - I^{bLS}\right) \rightarrow \Delta V = Z \Delta I$, it is obvious that the sensitivity of the voltage of bus j to the load current of bus i ($\Delta V_j / \Delta I_i$) is equal to $\left|Z_{j,i}\right|$, and this is the basic point of presenting this LS method. At first, the buses whose estimated voltages are lower than V_{crt} at t_{crt} are stored in CFs set, then, the location of LS is obtained through the index in (14). This index includes the voltage sensitivity of buses in CFs set to LS from each of the network's buses. Also, the voltage drop and power of IM loads are influential in choosing the location of LS.

$$loc = \max_{j=1,\cdots,N}\left(\sum_{i\in CFs} \frac{\left|S_{M,j}\right|}{\sum_{h=1}^{N}\left|S_{M,h}\right|}\left|Z_{i,j}\right| \times \left(V_{crt} - \left|V_{est,i}(t_{crt})\right|\right)\right) \tag{14}$$

After determining the location of LS, the bus whose voltage takes the greatest effect from LS is identified by Eq. (15). After determining MAF bus (Most Affected FIDVR), Eq. (16) is used to determine the amount of LS. As it is obvious, all parameters that can affect the intensity of FIDVR are used in this equation, and the way to obtain it has been explained in [34].

$$MAF = \max_{i\in CFs}\left(\left|Z_{i,loc}\right| \times \left(V_{crt} - \left|V_{est,i}(t_{crt})\right|\right)\right) \tag{15}$$

$$n_{LS}(\%) = \frac{V_{crt} - \left|V_{MAF}^{bLS}\right|}{\left|Z_{MAF,loc}\right|\left|I_{loc}^{bLS}\right|} \times 100 \tag{16}$$

3- Results of Simulation

Online LS methods based on the voltage estimation process described in this paper are implemented on IEEE 118-bus network. The percentages of IM and static loads in this network are 60 % and 40 %. The moment of fault occurrence is assumed as 1 s, and the critical time and voltage are determined as 1 s after the occurrence of fault and 0.8 pu, respectively. Also, the LS moments are 0.5, 0.7 and 0.9 s after the fault occurs. Studies on this network are carried out considering the following faults:

First fault: single-phase fault to the ground on the line between buses 11 and 13 at a distance of 70 % from bus 11 with a fault resistance of 7 Ω occurs at 1 s, and it is cleared 0.25 s later. Probably, the occurred FIDVR is not very intense.

Second fault: with the occurrence of a 3-phase fault in 50% of the line between buses 82 and 83 at the moment 1 s, the distance relays on both sides of the line clear the fault at the moment 1.05 s. The voltages of all buses except buses 82, 83, and 84 are greater than 0.8 pu at 1 s after the occurrence of the fault.

Third fault: with the occurrence of a two-phase to-ground fault on the line between buses 51 and 58 at the distance of 90% from bus 51 at the moment 1 s, the distance relays on buses 58 and 51 clear this fault in their zone 1 (0.05 s) and zone 2 (0.25 s), LS is necessary for preventing the interference of FIDVR and UV relays in such situations.

3- 1- Investigation about Voltage Estimation Tools

Previous methods such as [28] and [37] use the straight line to estimate the voltage in future moments to find out which buses have critical FIDVR. During the first fault, the estimation of voltage in this way for bus 13 is available in Fig. 6. It is clear that the measured voltage reaches a value greater than the critical voltage at the critical time, and in such a situation, there is no need to LS, however, the estimated voltage through straight line results in different conclusion; and methods [28] and [37] will shed unnecessary loads. The presented voltage estimation tool in [32-34], which is based on the modified Gauss-Seidel load flow and three-order model of IM, has a better ability to estimate the voltage and follow its' changes over time according to Fig. 7 because of use of load and network parameters. According to the results of the proposed voltage estimation tool, the central unit decides not to operate and shed the load for the first fault, although the voltage estimation using the straight line will result in unnecessary LS.

3- 2- Results Comparison of Proposed LS Methods

The obtained result for three proposed LS methods is presented in Table 1. The first proposed method suggests a lower amount of load to be shed from the network than the rest of the presented methods according to Table 1, however, the performance of this method is highly dependent on the pre-determined LS step. There is a possibility of increasing the load suggested to shed if large steps are chosen; on the other hand, small steps will increase the execution time of the method. Therefore, this method cannot be introduced as the most appropriate method among the proposed methods with certainty. The second method is presented in the form of an optimization problem in order to overcome the defect of the first method. This method suggests a greater amount than the first method for shedding from the network, also, the execution time of this method is longer than the first method; however, does not have the uncertainty of confusion in determining the LS steps, unlike the first method. The third LS method can determine the amount and location of LS by analyzing the sensitivity of voltages to the reduction of

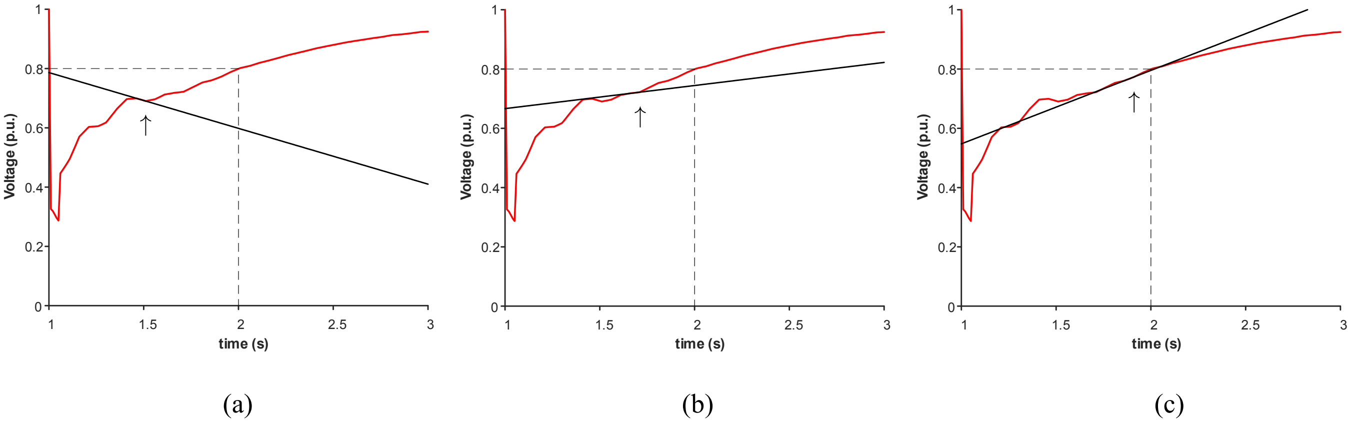

Fig. 6. Different slopes of the tangent lines to the measured voltage of bus 13 at the moment: (a) 1.5 s, (b) 1.7 s, (c) 1.9 s

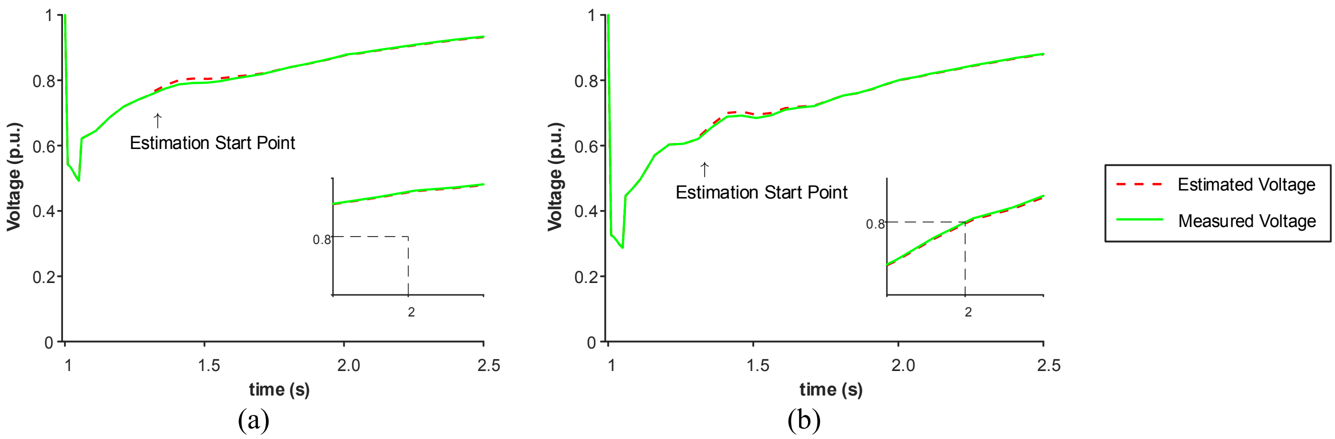

Fig. 7.Comparison of measured and estimated voltages through proposed voltage estimation tool for (a) bus 11, (b) bus 13

Table 1. Results Comparison of Proposed LS Methods

	First Proposed Method		Second Proposed Method		Third Proposed Method	
	Second Fault	Third Fault	Second Fault	Third Fault	Second Fault	Third Fault
Sum of Loads to be Shed	30 MVA	51 MVA	32 MVA	54 MVA	33 MVA	60 MVA
Total Time Calculation	0.07 s	0.12 s	0.10 s	0.15 s	0.03 s	0.05 s

load currents. The execution time of the third method is less than other proposed ones due to the simplicity of equations extracted for this method, however, it is less comprehensive than two other methods, and it offers more load than the other methods to shed from the network.

LS in the early moments of the FIDVR phenomenon helps to restore the voltage faster, therefore, disconnection of the least amount of load is not the only indicator regarding the optimal performance of LS method in the discussion of dealing with FIDVR, and attention should also be paid to the execution time of method and the number of moments when the studied method applies LS. In order for the proposed LS methods can deal with FIDVR by shedding the load only at the first LS moment, all calculations must be performed in the interval time between the start of voltage estimation (0.3 s after the occurrence of fault) and the first moment of LS (0.5 s after the occurrence of fault). According to the results listed in Table 1, all proposed methods have the ability to deal with the interference of FIDVR and UV relays by LS only at the first moment because the execution times of these methods are less than the time difference between the start moment of voltage estimation and the first LS moment. However, it should be noted that the execution time is not the only time delay expected in the studies, and other time delays such as data receiving and sending delay through telecommunication channels and the operation delay of switches should also be considered.

3- 3- Comparison of Methods in Real Conditions of Power Network

LS schemes do not actually have access to the loads, and the only way of applying LS is to disconnect the entire feeder from its beginning in the substation. In order to exactly determine which feeder should be disconnected from the network, it is necessary to model the loads of each of the feeders separately, which the efficiency of proposed LS methods will be lost in terms of execution time due to the high number of variables in such conditions. To solve this issue, it is proposed to replace the total loads fed through all outgoing feeders from each substation with the load model in Fig. 2. Applying this proposal will significantly reduce the number of variables and also the time of calculations, therefore, the proposed LS methods can be implemented in terms of execution time. After determining the location and amount of the load that should be shed, the disconnection trips are sent to the smart load switches at the beginning of feeders, and the feeders are disconnected along with all their loads.

In order to check the effect of feeder disconnection based on the results of proposed LS methods, it is assumed that each substation has 4 output feeders with load distribution equal to 10%, 20%, 30%, and 40%. After the proposed LS methods in Section 2-6 obtain the location and amounts of LS based on the modeling of total loads fed from the substation with the load model of Fig. 2, these amounts are applied to the network based on the amount of load that can be disconnected in reality. For instance, if the LS method has proposed shedding 75% of the load of one bus, 40%, 30% and 10% of feeders will be disconnected from the network, and in such situations, 80% of the load will be shed. Tables 2 and 3 contain LS amounts based on feeder disconnection for the second and third faults. If the results of the method [28] were applied to the network as a percentage-based LS, it would not be able to deal with critical FIDVRs; however, if LS is based on feeder disconnection, this method can also eliminate critical FIDVRs. The results in this situation illustrate the superiority of LS methods over conventional ones. Also, the first proposed LS method has better performance in the view of LS amount, however, the execution time of third proposed method is the least. The choice between these proposed methods depends on the power of processor used in the central unit to perform calculations.

4- Conclusion

In this paper, the requirements for the implementation of wide-area LS methods to deal with FIDVR are reviewed. In addition to paying attention to the appropriate methods to calculate the lowest load that can be shed from the smaller number of buses at the early moments of FIDVR, attention should also be paid to the ability of implement of proposed methods. The prerequisites for this implementation are the estimation of load parameters, detection of fault occurrence, detection of fault clearance, and detection of changes in the network topology. Achieving these prerequisites needs fast communication that can transmit information in the shortest possible time, therefore, it is suggested that the communication required by LS scheme conforms to IEC 61850 because this standard provides fast communication in the form of GOOSE message.

In the presented wide-area LS scheme, network information is sent by PMUs to the central unit, and the central unit decides how much load to shed from which bus at what time. The first method used an index based on IM loads' power changes for detecting the LS location. The LS amounts are considered fixed values, and the voltage estimation process validates these LS locations and amounts. The problem of LS to deal with FIDVR is modeled as an optimization problem in the second proposed method, and the results of this linearized problem are the location and amount of LS required to be applied to the network. The third method is also a sensitivity analysis method and its aim is simultaneous voltage recovery of all buses involved with critical FIDVR. Three proposed methods are implemented on the IEEE 118-bus network; by comparing the results of various LS methods, it has been concluded that the proposed LS methods have the ability to deal with FIDVR by shedding less amount of load from fewer buses and in the initial moments of occurrence of FIDVR. In other words, using the voltage estimation process has increased the intelligence of LS schemes compared to the existing LS methods.

Table 2. Results comparison of previous and proposed LS methods for second fault in real conditions

	First Proposed Method	Second Proposed Method	Third Proposed Method
First LS Moment	Feeders 30% & 40% from bus 83	Feeders 10%, 30% & 40% from bus 83	Feeders 10%, 30% & 40% from bus 83
Second LS Moment	-	-	-
Third LS Moment	-	-	-
Sum of Loads to be Shed	30 MVA	34 MVA	34 MVA

	Method [28]	Method [37]
First LS Moment	Feeder 10% from bus 82 Feeder 10% from bus 83 Feeder 10% from bus 84	Feeder 30% from bus 82 Feeder 30% from bus 83 Feeder 20% from bus 84
Second LS Moment	Feeder 20% from bus 82 Feeder 20% from bus 83	Feeder 10% from bus 83
Third LS Moment	Feeder 30% from bus 83	-
Sum of Loads to be Shed	42 MVA	38.5 MVA

Table 3. Results comparison of previous and proposed LS methods for third fault in real conditions

	First Proposed Method	Second Proposed Method	Third Proposed Method
First LS Moment	Feeder 40% from bus 51 Feeders 10% & 40% from bus 52 Feeder 30% from bus 58	Feeder 40% from bus 51 Feeders 20% & 40% from bus 52 Feeder 40% from bus 58	Feeders 20% & 40% from bus 51 Feeders 20% & 40% from bus 52 Feeder 40% from bus 58
Second LS Moment	-	-	-
Third LS Moment	-	-	-
Sum of Loads to be Shed	51 MVA	59.5 MVA	68 MVA

	Method [28]	Method [37]
First LS Moment	Feeder 10% from bus 50 Feeder 10% from bus 51 Feeder 10% from bus 52 Feeder 10% from bus 53 Feeder 10% from bus 57 Feeder 10% from bus 58	Feeder 10% from bus 50 Feeder 20% from bus 51 Feeder 20% from bus 52 Feeder 20% from bus 53 Feeder 10% from bus 57 Feeder 20% from bus 58
Second LS Moment	Feeder 20% from bus 51 Feeder 20% from bus 52 Feeder 20% from bus 53 Feeder 20% from bus 58	Feeder 30% from bus 51 Feeder 30% from bus 52 Feeder 30% from bus 58
Third LS Moment	Feeder 30% from bus 51 Feeder 30% from bus 58	-
Sum of Loads to be Shed	85 MVA	81 MVA

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