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Development and Real-Time Implementation of an Under Voltage Load Shedding Scheme Using a Real-Time Digital Simulator

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Abstract – *Generation, transmission, and distribution of electric power systems are extremely important to our modern society. It is critical to keep the power grid stable and reliable at all times. Individual power system reliability needs to be enforced to avoid a voltage drop due to contingencies such as a loss of generation or a sudden increase in a load demand. Voltage changes for a given increase in the load demand can lead to voltage instability conditions. The main factor causing instability is the inability of the power systems to meet the demand of the reactive power. This subject has been a concern over the last two decades and a lot of research work has been done in the area of voltage stability and control. Under-voltage load shedding schemes are commonly implemented as an emergency measure in cases where the voltage conditions are drastically dropping due to a sudden increase of the load demand in the system. This paper addresses the problem of designing and developing a robust and efficient Under-Voltage Load Shedding (UVLS) scheme for a real-time implementation in the power system networks. A new multi-stage adaptive UVLS scheme is developed in order to improve the operation and increase reliability and flexibility of the existing UVLS schemes. This scheme is implemented in real-time using RSCAD software environment of the Real-Time Digital Simulator (RTDS).*

***Keywords**: Power System, Load Shedding Scheme; Protection Relays, Intelligent Electronic Devices (IEDs), Under-Voltage Load Shedding Scheme, Real-Time Digital Simulator (RTDS)*

Nomenclature

E_S	Source voltage
F	Ratio of line and load impedance with their phase angles
I	Current
P_R	Active power supplied to the load
$P_R + jQ_R$	Complex power consumed by the load
P_{RMAX}	Maximum active power transfer at unity power factor
$P-V$	Power-Voltage
Q_R	Receiving reactive power
V_R	Received end voltage
V_S	Sending end voltage
V	Voltage
Z_{LD}	Load impedance
Z_{LN}	Line impedance
$\angle$	Angle formed by two-rays
φ	Phase angle of the load impedance
θ	Phase angle of the line impedance

I. Introduction

The stability of the power system is its ability to return to its normal operation after it had been subjected to some form of disturbances. The Electrical network systems were built many years ago, and now one of the major problems they are facing is the high growth of the power demand. It causes the power network to operate constantly at its maximum limits, leading it to instability. The modern power systems are widely interconnected, which results in a reliability problem. The wide interconnection of subsystems' stability problems has become an important challenge to power system engineers [1]. When there is a deficiency in power generation due to excessive load demand, the voltages at the buses drop causing voltage instability. In this case the reactive power demand is higher than the supplied one, and therefore by reducing some of the loads or disconnecting some of the non-critical loads, the system stability can be saved. The load shedding provides a low-cost means and should be the last resort to prevent a widespread system collapse.

The problem for the development of Load Shedding Schemes (LSSs) has been studied for many years both for utility power systems and industrial plants with in-house generation. Different methods have been used to achieve load shedding schemes in the power system networks [1]-[42]. These methods can be grouped as follows: optimization- based, index-based, adaptation-based and protection equipment-based.

The rest of the paper is organized and developed as

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follows. Literature review is presented in Section II, The basic concepts related to the voltage stability are discussed in Section III, Section IV describes the proposed methodology for power system stability margins determination, the real-time implementation of the methodology for determination of the voltage stability margin is presented in Section V, Section VI describes the development and implementation of the Under Voltage Load Shedding (UVLS) scheme and the discussion of the results from the real-time RTDS simulation is given in Section VII, and Section VIII presents the conclusion.

II. Literature Review

The following is a brief description of some methods and algorithms proposed in the relevant literature.

Optimization-based load shedding methods:

- In [2], an optimal load shedding method in the case of generation deficiency was proposed. The objective was to minimize the amount of load when the total generation is less than the total demand. The method was based on minimizing the system loss under the constraints on generator limits and line flow limits. The method calculated the loss coefficients using Kron's matrix transformation technique;
- In [3], a neural network-based methodology to develop load shedding schemes for industrial power systems was proposed. The paper used neural networks to establish complex mappings between the post-disturbance network configuration and the amount of load to be shed. The proposed method was tested on the power system of a petrochemical plant in order to see the effectiveness of the scheme;
- A priority-based load shedding for distribution networks in the presence of DG units was proposed in [35]. A robust Hybrid Islanding Detection Technique (HIDT) was proposed for identifying the islanding event early. The priority -based load shedding had to be implemented in the islanded area if the power supply is not enough in order to maintain a reliable supply to the customers. MATLAB R2010a and Power System Analysis Toolbox (PSAT) simulations for the cases of IEEE 33 and 69 bus distribution systems under different loading conditions. The testing of the load shedding algorithm is done only by off-line simulations;
- An optimal load shedding strategy for power systems with Distributed Generation (DG) was developed in [4]. The DGs were considered to be 3 types: a central generation, a non-dispatchable and a storage one. Dynamic and static discrete models of each type DG were developed and used to calculate an optimization solution for operation and security constraints of the Load Shedding Scheme (LSS);
- In [39] an islanding detection and optimal load shedding scheme were developed for a radial distribution system that was integrated with dispersed generation. A probabilistic neural network-based classifier was developed for a passive islanding detection. In a case where unintentional islanding state was detected, an optimal load shedding scheme, based on backtracking search was utilized to prevent the system from being exposed to voltage instability. An IEEE 33-bus system with four DG units was used to validate the algorithms in Dig Silent Power Factory® and MATLAB® software;
- A new load shedding scheme for Islanded Power Systems (IPS) was presented in [5]. The objectives were to maximize various system benefits and minimize the load curtailment. An Analytic Hierarchical Process (AHP) was adopted for prioritizing the loads. It was based on the changing priorities and the critical nature of the loads;
- A new event-driven emergency load-shedding scheme is presented in [36]. An Optimal Event-Driven Load-Shedding (OEDLS) model was developed. The algorithm was based on linearizing the nonlinear OEDLS model through trajectory sensitivity. Parallel computation scheme to accelerate the problem-solving process is used. The proposed algorithm was tested and validated using Computing Toolbox in MATLAB and the PSS/E software;
- In [6] an algorithm, based on two sub-problems, namely restoring solvability and improving the Voltage Stability Margin (VSM) of a power system were developed to achieve voltage stability through load shedding. The two problems were solved by Linear Optimization (LO)-based Optimal Power Flow (OPF) method. The constraints of using this algorithm are that it is based on the local optimum and does not guarantee a global optimum;
- An efficient load shedding techniques for a distributed system was presented in [7]. The distributed load shedding problem was modeled as a linear optimization problem. Two alternative solutions for this problem were proposed, namely: a solver-based centralized approach and a distributed approach based on metadata aggregation and propagation. The solutions were based on generating a series of load shedding plans in advance, to be used under certain input load conditions;
- In [29] a predictive control model, based on the reactive power from the generator and on the voltage magnitude was developed. The operation and the amount of loads to be shed are determined by the severity of the system contingency;
- UVLS scheme that was technically integrated to minimize the financial losses when compared to a complete blackout was proposed in [32];
- In [33] a UVLS algorithm using a Mixed Integer Programming (MIP) method was developed. A model that uses a mixed-integer linear formulation to provide voltage stability was used. Simulations were performed for the cases of IEEE 14-bus and IEEE 118-bus test systems. The same test systems were used to compare the proposed MIP-based UVLS model and the original non-linear programming UVLS model. The proposed algorithm was based on UVLS model

with a predetermined value of loading margin and with minimum amount of load to be shed;

- Three different load shedding schemes - voltage-based, timer-based and combined, applied in a direct current (DC) microgrid were compared in [40] using the PSCAD/EMTDC software. The results showed that the voltage-based and timer-based load shedding schemes caused a drop of the bus voltages lower than their limits. The timer-based load shedding caused over shedding of loads. This degraded the power supply reliability. It was also discovered that the combined methods increased the power supply reliability in relation to the critical loads and also prevented over shedding of the loads.

Index-based load shedding methods:

- In [8] a new load control strategy called Distributed Interruptible Load Shedding (DILS) was developed with the aim to guarantee a correct electrical system operation. It was based on controlling the loads individually;
- A Power Transfer Stability Index (PTSI) algorithm based on Fixed Shed Fixed Delay (FSFD) and Variable Shed Variable Delay (VSVD) approaches was developed in [9] in order to avoid the voltage collapse. The objectives were to maintain the stability and survivability of the power system under major faults and for variety of the system configuration topologies. A Matlab Power System Analysis Toolbox was used to perform simulations. In [10] a redundant load shedding system for islanded power plants was presented;
- A Fast Voltage Stability Index (FVSI) method assisted by a Photovoltaic (PV) analysis algorithm for numerical verification of the locations where the loads need to be shed in the power system was developed in [11]. A Power System Simulation for Engineers (PSSE) software was used for modeling. The constraints of this method are that it has focused only on the static behavior of the system;
- A Linearized Optimization Method (LOM) and a Binary Integer Programming (BIP) algorithm for handling the discrete loads were proposed in [13]. An active and reactive power (P, Q) Voltage Stability Index (PQVSI) was used to measure the system conditions. The software used is the Sequential Quadratic Programming (SQP);
- A Fast Voltage based Stability Index (FVSI) approach to indicate the load condition for UVLS scheme was applied in [17]. The software used was PSCAD. The constraint of the paper is that no real-time simulation package was used to validate the performance of the FVSI;
- A probabilistic UVLS scheme was developed in [24]. A Point Estimate Method (PEM) algorithm was developed to convert the probability distribution functions (PDFs) of load uncertainty to discrete statistical moments which present the behaviors of the original continuous PDFs. The proposed UVLS strategy is expressed as a non-linear programming problem solved by sequential quadratic programming. The developed algorithm was compared with Monte Carlo simulation algorithm. The IEEE 14 bus and IEEE 118 bus systems were used to test, validate and compare the algorithms.

Adaptation-based load shedding methods:

- In [12] an adaptive load shedding technique for controlled islanding was developed. Optimization techniques based on Model Predictive Control (MPC) and Monte Carlo methods to determine the optimal load shedding value for an abstract model equipped with a conventional load shedding mechanism were used;
- The impact of the integration of Distributed Generation (DG) in distribution grids on the load shedding was investigated in [14]. All challenges and operating problems when DGs are connected in low and medium voltages in power systems were considered. It was discovered that a significant increase of integration of DG units in distribution grids can lead to major planning issues and conflicts with the legal and regulatory frameworks;
- A computerized technique for controlling a load-shedding scheme was developed in [15]. The objective was to minimize the manual work by selecting the feeder, substation, and duration of shedding time by the user. The proposed model was simulated to verify its suitability. The algorithms open a door for fast Load Shedding Controller (LSC) designs with low cost, convenience, scalability, and remote access capability;
- Model Predictive Control (MPC) algorithm was used in [16] to develop an adaptive under-voltage load shedding scheme. A sequential quadratic programming technique was used for the design of the MPC controller;
- An adaptive trajectory sensitivity index algorithm to determine the minimum amount of load to be shed was developed in [18];
- In [25] a centralized adaptive wide-area load shedding scheme that was incorporated into power system real-time limitations was proposed. The developed algorithm has three stages. The first stage determines the requirements needed for implementation. The second stage specifies the optimal amount and location of load to drop and posts load shedding strategies. It also accommodates all operational limits and considers the interruption cost for the shed loads. The third stage determines the event type in real-time. A fuzzy decision-making method based on measurements, gathered from the power network was developed. An IEEE 39 Bus system was used to conduct the study;
- In [37] an adaptive voltage-based load shedding scheme for the DC Microgrid was proposed. Voltage threshold algorithm was used based on the rate of change of locally measured bus voltages. Simulations were conducted using PSCAD software. The following points were achieved: (i) the DC microgrid

power balance was effectively maintained through fast and coordinated load shedding, (ii) the DC bus voltages were prevented from falling below acceptable levels, (iii) the critical loads do not experience excessive steady-state voltage deviations, (iv) minimizes the durations and magnitudes of the temporary voltage drop caused by sudden disturbances, and (v) improves power supply reliability.

Protection equipment-based load shedding methods:

- In [26] an adaptive tuning of frequency thresholds using voltage drop data in decentralized load shedding is proposed. Protective relays were installed at different locations and used to measure and monitor all local voltages. The developed algorithm was programmed in DIgSILENT Power Factory software environment and tested by simulation. No real-time implementation. An IEEE 39 bus system was used to validate the algorithm;
- A conventional UVLS executed by protective relays was introduced in [27] using a Voltage Stability (VS) violation algorithm based on decentralized configurations. The relays were configured to operate at fixed time delay and threshold voltage. This method leaded to unnecessary load shedding and the system experienced overvoltage;
- An UVLS scheme that adopted the least square curve fitting algorithms to calculate the number of loads that need to be shed during abnormal conditions was developed and implemented using Phasor Measurement Units (PMU) in [28]. It was determined that the implementation of the schemes using PMUs provided for the case of Wide Area Networks faster measurement, detection of the voltage instability and implementation of the load shedding;
- In [30] a new Special Protection Scheme (SPS) in order to mitigate voltage collapse against predetermined contingencies is developed. The new SPS algorithm utilizes the Voltage Stability Margin (VSM) of the system. The load shedding scheme optimizes the load to be shed and minimizes the deviation from the nominal voltage. The algorithm also uses the fuzzy-based theta gravitational search techniques. A power system from Khorasan area in Iran was used as a case study. It was simulated in PSS/E software;
- Global and local strategies for load shedding with an idea to preserve the energy supply to high priority loads within quality standards was presented in [31]. The developed algorithm for the load shedding scheme is based on three fundamental premises: includes both active and reactive powers at each bus, the whole load in a bus is shed and the decision of load shedding is implemented before the actuation of voltage and frequency protective devices. A Monte Carlo simulation was used to validate the proposed algorithm. An IEEE 37 Node Test Feeder was used to conduct the study;
- In [34] an automation scheme for emergency operation of a multi-microgrid industrial park was proposed. A hybrid under-voltage/under frequency islanding scheme was developed. The scheme was based on multi-step methodology where predefined sets of lower priority loads need to be shed in order to stabilize the system;
- In [38] a new under-impedance load shedding (UILS) scheme was presented. The proposed method used a quadratic distance relay. The concept was based on monitoring the trajectory of load impedance by the proposed UILS relay. The new under-impedance load shedding scheme was tested on various networks, including a real power system model. Based on the results UILS was proving to operate efficiently.

Today's engineers encounter a variety of problems when consider the design, operation, and control in power systems. Power system network needs to be reliable, stable and supply power continuously without any interruptions. One way of solving such a problem is by using adaptive load shedding schemes in order to keep the power system stable even when the power supply is less than the load demanded level at that particular time. The analysis of the literature on the main approaches for development of Under Voltage Load Shedding schemes leads to the following conclusions:

- Most of the approaches are theoretical and based on various types of Mathematical programming optimization methods. The proposed algorithms are validated only by static simulations. The real- time conditions of the power network are not taken into consideration, which is a serious drawback of the current literature as the load shedding requirements appear during the dynamic behavior of the network. Not effort is made for development of dynamic models and methods;
- The same problems can be seen in the literature considering voltage stability indexes and proposing adaptive Under Voltage Load Shedding schemes. The utilities and industry prefer the new developed methods and algorithms and feasibility study to end up with a practical implementation for the testing and validating of the results;
- The other drawbacks with the existing schemes are the lack of adaptation towards the disturbances and the behavior of the system during the period of instability. UVLS schemes still have not found a good solution when the correct amount of load to be shed has to be determined, to select the type of load to be shed and to reduce the execution time of the load shedding operation;
- The problem for Under Voltage Load Shedding schemes development for the case of multi-area interconnected power systems is considered in a little number of papers as for example [28] and the real-time implementation of the UVLS schemes for multi-area power systems is not considered;
- The recent literature describing the protection equipment-based load shedding methods has a realistic approach and considers implementation of new under voltage algorithms (more complex than the

protection ones) to be implemented in real devices as protective Intelligent Electronic Devices and Phasor Measurement units. Some of the proposed algorithms are simulated in real-time, but some papers use again steady state type of simulations;

- The traditional ways of the power system networks simulations have disadvantages when compared to the real-time simulation. One of the most noted disadvantages is the speed of executions of the simulation. The advantage of using a real-time simulator is the fact that it can be integrated with the physical equipment, and studies such as closed-loop testing of protection relays can be implemented;
- The real-time simulator can be used to connect to the physical equipment and run the power system simulation in real-time to test the performance of the used devices. It opens a large spectrum of possibility to provide a range of advanced tests that are required by the power utilities.

The proposed adaptive load shedding scheme is designed based on the understanding of how the generation up to the load demand operates in real-time. The intention is to overcome the drawbacks of the existing in the literature and industry UVLS schemes as listed above by proposing a new scheme capable to be implemented in real-time. The aim of this paper is to develop and implement in real-time an adaptive Under Voltage Load Shedding (UVLS) scheme for a distribution multi-area power network. The proposed fully decentralized adaptive multi stages UVLS controllers are implemented in soft Intelligent Electronic Devices (IEDs) in the RSCAD software environment of the Real-Time Digital Simulator (RTDS). The performance of the developed dynamic closed loop adaptive UVLS scheme is evaluated in real-time under various load contingencies.

Deliverables of the paper are as follows:

1. The existing model of the IEEE 39 bus system is represented as a four-area interconnected power system model. This model is programmed in the RSCAD, the software environment of the Real-Time Digital Simulator (RTDS) and load flow simulation in real-time is performed;
2. Methodology for power system stability margins determination based on the use of the P-V curve dependencies and the RTDS application is developed;
3. Real-time implementation of the methodology for determination of the voltage stability margins is performed in the RSCAD software environment of the RTDS;
4. A new controller of the process of gradually load increase in order to create load contingency in the RSCAD environment is developed. The contingencies that lead the power system to instability are investigated;
5. New algorithm for adaptive UVLS scheme based on a multi-stage load shedding operation and on prioritization of the amount, order and location of the loads to be shed is developed;
6. New multi-stage decision making logic algorithms and load shedding logic controllers for the decentralized type implementation of the adaptive load shedding process in the real-time environment of the RSCAD/RTDS are developed;
7. Soft Intelligent Electronic Devices (IEDs) to implement the multi-stage decision making logic algorithms and the load shedding logic controllers are developed and implemented in the RSCAD/RTDS environment;
8. A new closed loop adaptive under voltage load shedding scheme to return the network to stability is developed and implemented in the RSCAD/RTDS environment. The performance of the multi-area power systems is investigated during the load contingencies and the control action of the UVLS scheme and the obtained results are analyzed.

III. The Basic Concepts Related to the Voltage Stability

The voltage stability analysis in power systems involves two aspects. The first one is proximity to voltage instability. This aspect deals with how close the system is to voltage instability, supposed it operates at a particular loading condition and starts to become voltage unstable at a critical load condition. The questions are: at what point of loading the system starts to be unstable and what is the distance between the stable and unstable statuses of the system? The second aspect is to find out the reasons, the key factors and the mechanisms of voltage instability, meaning how and why the instability occurs. On the basis of the above investigations, the most effective measures for improving of the voltage stability have to be determined. There may be certain portions of the system that are more prone to voltage instability. These voltage weak areas have to be determined in order correct measures to be taken to make these areas stronger by either injecting or installing more sources of reactive power. The paper gives answers to the above questions by development of a UVLS scheme on the basis of the fundamental dependencies between the voltage, power, and current in power networks with loads and proposes methods and algorithms for real-time implementation of the scheme.

III.1. Fundamental Dependencies in Power Networks with Loads

In order to understand the basic features of the concepts of voltage stability, a basic power network shown in Fig. 1 is considered [19]. The network consists of a voltage source $\overline{E}_s = E_s\angle 0°$ connected to a load whose impedance is $\overline{Z}_{LD} = Z_{LD}\angle\phi$ and this load is supplied through a transmission line whose impedance is denoted as $\overline{Z}_{LN} = Z_{LN}\angle\theta$ where ϕ is the phase angle of the load impedance and θ is the phase angle of the line impedance.

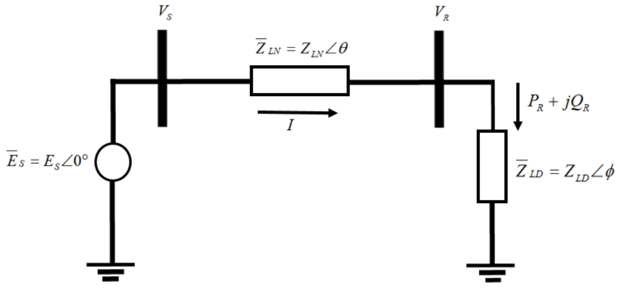


Fig. 1. The basic power network [19]

The complex power consumed by the load is denoted as $P_R + jQ_R$. The objective is mathematically to derive all variables of the power network that influence the voltage stability in order to receive better understanding of the mechanisms leading to voltage instability, so that an adaptive algorithm for improving voltage stability can be developed. The first step is to derive a mathematical expression of the received voltage V_R in terms of the various parameters of the network. The current $\bar{I}$ that flows in this network is written as the voltage $\bar{E}_S$ divided by the sum of the two impedances $\left(\bar{Z}_{LN} + \bar{Z}_{LD}\right)$ as shown in Eq. (1) below:

$$\bar{I} = \frac{\bar{E}_S}{\bar{Z}_{LN} + \bar{Z}_{LD}} \tag{1}$$

The expression for the magnitude of the current I can be written in terms of the source voltage E_S divided by the parameters of the line and the load impedances as shown in Eq. (2) below [19]:

$$I = \frac{E_S}{\sqrt{\left(Z_{LN} + \cos\theta + Z_{LD}\cos\phi\right)^2 + \left(Z_{LN} + \sin\theta + Z_{LD}\sin\phi\right)^2}} \tag{2}$$

Further the current I in (2) can be expressed as:

$$I = \frac{1}{\sqrt{F}} \cdot \frac{E_S}{Z_{LN}} \tag{3}$$

where F is defined as:

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right)^2 \cos(\theta - \phi) \tag{4}$$

Now the magnitude of the voltage at the load end can be written as:

$$V_R = Z_{LD} I \tag{5}$$

The next step is to substitute current I in (5) by its expression in (3) and V_R is then obtained as:

$$V_R = \frac{1}{\sqrt{F}} \frac{Z_{LD}}{Z_{LN}} E_S \tag{6}$$

The real power P_R received by the load is expressed as follows:

$$P_R = V_R I \cos\phi \tag{7}$$

Substituting V_R in (7) with its expression from (6), equation (8) is developed:

$$P_R = \frac{Z_{LD}}{F}\left(\frac{E_S}{Z_{LN}}\right)^2 \cos\phi \tag{8}$$

The three variables: the voltage across the load V_R, the power P_R and the current I which are drawn by the load are derived. Therefore, it is necessary to plot the variations of these three variables in order to understand the voltage stability concept in the power system networks. The receiving end voltage, power and current are represented in terms of per unit values on the y-axis and the normalized impedance Z_{LN}/Z_{LD} on the x-axis of the graph shown in Fig. 2. The graph helps to explains three different operating conditions that lead to voltage stability problems in power system distribution networks. These conditions are normal, critical and abnormal operations. In a scenario where the load demand increases the Z_{LD} decreases causing P_R at first to increase rapidly for some time while V_R decreases.

At a point in the graph where P_R is intersected by V_R, the system is said to be stable and operating normally although the voltage V_R has dropped from 1pu to 0.8pu.

After this intersection point P_R increases slowly before reaching its maximum value.

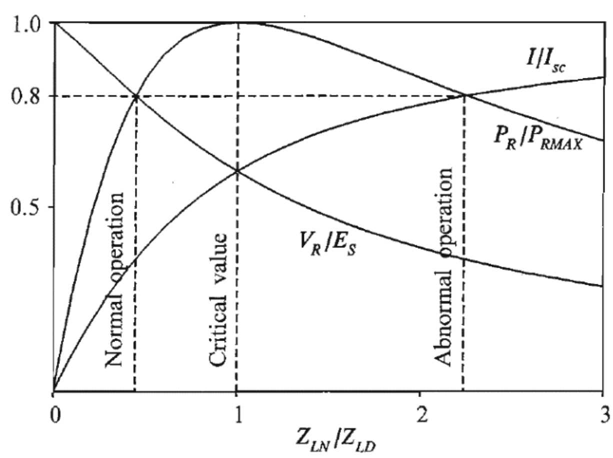


Fig. 2. The plots for I, V_R and P_R [19]

The graph shows that P_R is at a maximum when the ratio of $Z_{LN}/Z_{LD} = 1$ and the magnitude of the voltage drops across the transmission line. At a point where P_R is at the maximum value, the operation conditions are known to be at a critical point, meaning that the system is still within its limits. If Z_{LD} becomes less than Z_{LN}, then V_R will continue to decrease and I will increase. Decrease of V_R dominates the increase of V_R and therefore P_R will decrease. At a point where P_R intersects I, an abnormal condition in the system is declared. At this point, the system is unstable [19].

III.2. Power Voltage (PV) Characteristic Curve

The $P-V$ characteristic curve is generally the relationships between P_R, V_R and the reactive power injection Q_i.

Supposing that Q_i is injected into a system, then the $P-V$ characteristic curve is used to understand how the variations of V_R and P_R influence the system. The effects of V_R and P_R are analyzed based on $P-V$ the characteristic curve as shown in Fig. 3 [19]. The graph shows that if $P_R = 0$, $V_R = E_S$ and $\frac{V_R}{E_S} = 1$. As the P_R increases, the V_R decreases and it comes to a point $P_R = P_{RMAX}$ where P_R reaches a knee point and V_R drops. When P_R has to be increased beyond this critical point, the system is no longer in a position to increase the power, and therefore P_R and V_R decrease.

At the critical point, the system starts operating in an unstable condition [19]. On the basis of the above considerations, it could be concluded that the stability of the power networks with load depends on the load behavior in real-time and at specific values of the load the networks become close to instability or become unstable.

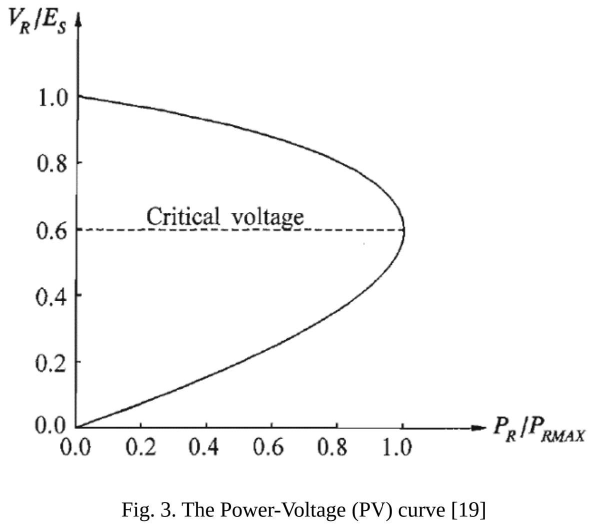


Fig. 3. The Power-Voltage (PV) curve [19]

The two points of the voltage - of the critical value and abnormal value determine the low voltage transfer limits and the voltage collapse points. Before the development of any voltage load shedding algorithms for a given system, these points have to be determined. A methodology proposed to determine in real-time these Power Margins (PM) of the whole network is described in the next section of the paper for the case study of the IEEE 39 bus system described in [22].

IV. Methodology for Power System Stability Margins Determination

The objective is to use the PV curve in Fig. 3 to calculate the voltages at the buses of the considered network with respect to the active power of the loads. A PV curve is built and analyzed in order to develop the Power Margins (PM) of the whole system. A case study is performed by a real-time simulation which considers all events that lead to voltage instability. A normal load flow using RTDS simulator was executed; all the data required for the analysis were measured and examined for the different areas of the system. The procedure proposed for developing of the PV curve is based on the following:

- The study focused on the real power at the load points. A constant power factor was assumed for this study;
- The real power of the loads at the network areas was modelled at different voltage levels. This exercise was done to provide an ideal condition for the PV curve analysis. The idea is based on the PV characteristics that when the real power of the loads is scaled up, the operating point at the PV curve is anticipated to drop until it reaches a point where the voltage collapses. The effect of increasing the real power of the loads is that the voltages dropped;
- The bus voltages at various areas of the system are monitored as the load real power was increased. The bus voltages are monitored until their maximum limit of 0.95pu is reached. This means that the real power that corresponds to this voltage is at its maximum. Therefore, the load is at its maximum as well;
- The above point is achieved by automatically increasing the loads of the system;
- The PV curve is based on plotting voltages, against power at the critical busbars. The monitored bus voltages data are presented on the y-axis and the x-axis represents the real power data of the loads.

The above procedure is performed for the case of the IEEE 39 bus power system which is modelled and simulated in the real-time software environment of the Real-Time Digital Simulator (RTDS). The practical implementation of the procedure is following the steps:

- Building a model of the IEEE 39 bus system as a four-area interconnected power system in the RSCAD software environment of the RTDS;
- Calculation of the load flow for the network to establish the base case in which the system is stable and the voltages of the load buses are in the normal margins;

- Developing a credible load contingency to disturb the power network;
- Defining the main parameters for calculation of system voltage stability margins;
- Determination of the system voltage stability margins from the base case and the entire creditable contingency.

Implementation of the above steps of the investigation is described below.

IV.1. Building a Model of the IEEE 39 Bus System in the RSCAD Software Environment of the Real-Time Digital Simulator (RTDS)

RTDS Technologies introduced the world's first fully digital real-time power system simulator in 1989. The simulator has been developed to suit a wide variety of power system applications [23]. The RTDS performs real-time electromagnetic transient simulations to determine the behaviour of the systems under study. It has a digital parallel processing hardware architecture that is capable of simulating a small or large and complex power networks in real-time. Today the simulator is the world's benchmark for performing real-time power system simulations. This simulator leads the way for protection and control system Hardware-In-the –Loop (HIL) testing.

RTDS has penetrated to the power utilities as well as the research institutions for testing and commissioning of the electrical equipment. The advantage of using the RTDS is that it created a platform where it is safe for a human to test and control schemes that are used in power systems. It also provides a cheaper and safe way to study power system concepts that are dangerous and costly to be implemented in the real existing network. The IEEE 39 bus system was analyzed using the RTDS platform. This system consists of 39 buses, 10 generators, 19 loads, 34 lines and 12 transformers. This network was first presented in 1970 as a base model for power flow analysis and since then it has been used for scientific research and publications for many different research purposes. The network model consists of the following voltage levels 345kV, 138kV, 230kV, and 16.5kV respectively and runs at a normal frequency of 60Hz. The IEEE 39 bus system is considered in this study as a multi-area system and is presented as an interconnected 4- area system. Every area is modeled in a separate rack of the RTDS as shown in Fig. 4. This 4-area representation helps the software development in the simulator and gives possibilities for better understanding of the dynamic behaviour of the network. The modeling of the IEEE 39 bus system is done in such a manner that the RTDS rack1is hosting Area B, rack 2 is hosting Area D, rack 3 is hosting Area A and rack 4 is hosting Area C respectively. This was done to accommodate the processor's cards that are used by the RTDS. The model of the network is built in the RSCAD/Draft module. This part of the software produces a window where on the left-hand side the new power system is modeled and as well as the rack number in which the simulation will be operated is given. On the right-hand side, the RSCAD functions library is shown.

The next step of the building of the model is the compilation of the new developed in RSCAD/Draft model.

Once the power system successfully is compiled, a "Run the simulation case" tab can be opened using the RSCAD/Runtime module. In the runtime module, a flexible platform is produced where the plots and simulation results can be analysed.

IV.2. Calculation of the Load Flow

Load flow study (also known as a power flow) is a pre-requisite for any studies in power systems. Power flow studies involve calculating the voltage magnitude and angle at each node or busbar of the network as well as its real and reactive powers. This paper elaborates the effect on power system stability when exposed to some contingency in order to understand how to modify an existing network in the most economical way to cater for the load demand increase or additional loads. It also helps to investigate the effect of loss of generation or loss of transmission lines.

The RTDS real-time simulations were done to find out the power flow on various transmission lines in order to monitor the system if it is within the limits of the carrying loading capacity of the transmission lines. It is also used to check if the voltages at all busbars are within the specified limits. Normally these limits can be plus minus five percent or ten percent from the nominal voltages depending on whether the load flow study is done for a high voltage system, the consumer level, or the voltage region.

The method of the PV curve is applied to find the critical operation point before the voltage instability occurs in the power system. A PV curve determines the transfer limits which are accountable for the voltage and the active power flow functions. The PV curve operates in such a manner that when the active load power transfer is increased, the voltage at some buses decreases. As the power transfer capacity increases the voltage at the buses decreases until it reaches the low voltage criterion known as the low voltage transfer limit.

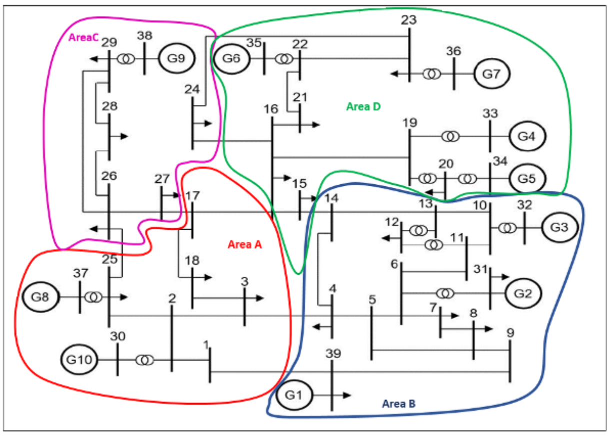


Fig. 4. One-line diagram of the 4-area IEEE 39 bus system [22]

Fig. 5 elaborates the relationship between the receiving end voltage which is at the loaded bus and the load power transferred as an increase of the active power. The relationship between these components develops a PV curve for the considered system. PV curve is a useful tool for setting the performance of a network under conditions of increased loads indicating how much the demand can be scaled up and what the critical point in the network is.

IV.3. Development of Credible Contingencies

The power flow simulation provides information for the base case of the study and then the Voltage Stability Margin (VSM) for the system has to be determined in order to perform the voltage stability analysis. The method used in this simulation is based on calculating the PV curve which is developed through manipulation of the power transfer to the loads with defined step size increment for a series of AC load flow calculations while the bus voltages, generator outputs and the branch flows of the system are monitored. The rising of the load power transfer is considered as a contingency whose increase brings the power system to the area of instability.

An analysis of the results from the simulations is performed in order to identify the limitation of the power system under study. Two factors are considered when defining the VSM of the network under study. These factors are as follows:

- Performance levels of the power network components;
- Disturbance (loadability) simulations.

The definitions of the parameters for calculation of the voltage stability margin are derived from Figs. 1 and 2 where I V_R P_R Z_{LN} and Z_{LD} are used.

V. Real-Time Implementation of the Methodology for Determination of the Voltage Stability Margin

V.1. Calculation of the Load Flow and Load Flow Study Results for the Initial Base Case

The power flow study is done using RTDS/RSCAD in the draft module to find out the power flow on various transmission lines in order to monitor the system and analyze if it is within the limits of the carrying loading capacity of the transmission lines.

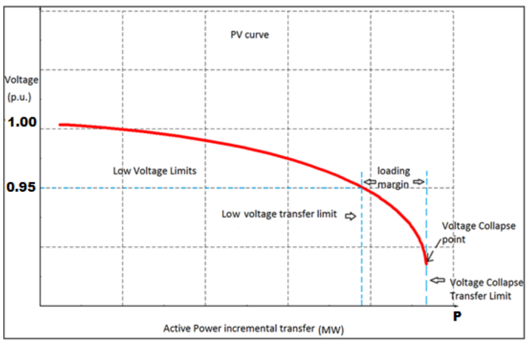


Fig. 5. The Developed PV curve

It is also used to check for the voltages at all busbars and to check if the voltages at all points are within the specified limits from 0.95pu to 1.05pu. The results at this point include the active power of generators for all four areas. They are recorded and the runtime module is used as the tool to analyze the results. The results at this point also include the voltage profiles as in Fig. 5 for all load buses and the total supply of all generators versus all amount of loads for this initial condition. Area B load bus voltages results are shown in Fig. 6. The system is stable at this point because the voltage limits are not violated.

It can be seen from Fig. 6, that six load voltages at Bus 04, Bus 07, Bus 08, Bus 13, Bus 31 and Bus 39 are monitored. The active powers of the loads are PL4= 500MW, PL7= 233.8MW, PL12=7.5MW, PL31= 9.2MW, and PL39=1010MW respectively. The load bus voltages are all within the voltage limits of 0.95pu to 1.05pu. Fig. 6 also shows the initial load, the demand, and the supply of the three generators PG1, PG2, and PG3. The frequency of the three generators is monitored too.

Although at this point only three generators out of the ten are presented, it is important to note that they are all synchronized and operating with the same speed. These generator frequencies were therefore considered as the system frequency.

The same procedure was done to record the results for the other three areas. Fig. 7 represents the results for the Area D which is modeled in RTDS rack 2. Area D is divided into two parts. The first part results are shown in Fig. 7 and the second part ones are shown in Fig. 9. Fig. 7 shows the results for the load bus voltages Bus15, Bus 16, Bus 20, and Bus 21 respectively. It can be seen that the voltages limits are not violated. Two generators are located at Area D and they run at a synchronous speed of 60Hz. Fig. 8 shows the results for the Area A.

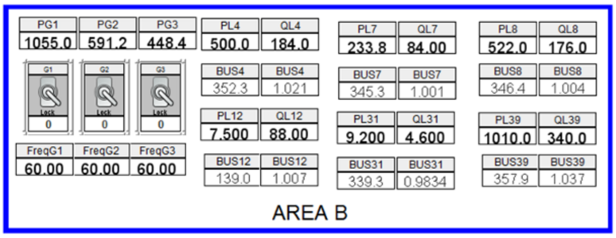


Fig. 6. Load flow results RSCAD/Runtime for Area B in RTDS rack 1

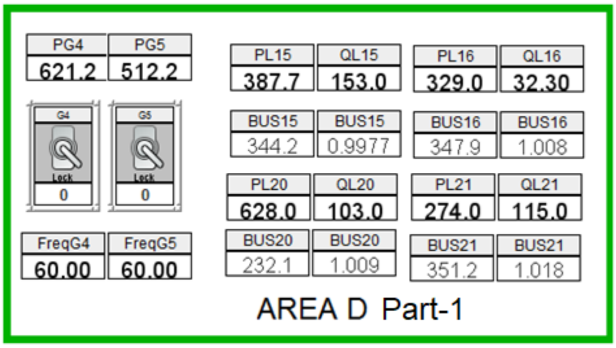


Fig. 7. Load flow results obtained in RSCAD/Runtime for Area D in rack 1

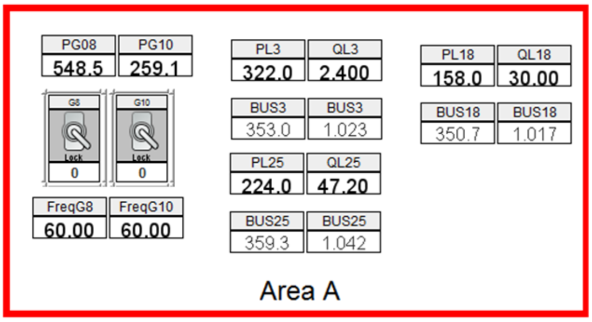


Fig. 8. Load flow results obtained in RSCAD/Runtime for Area A in rack 3

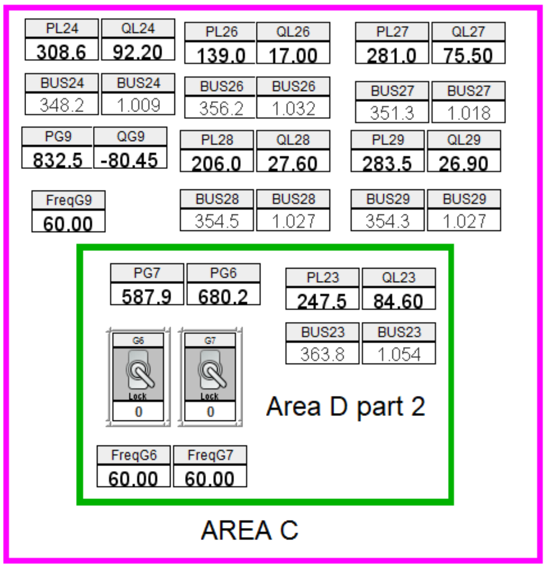


Fig. 9. Load flow results obtained in RSCAD/Runtime for Area C in RTDS rack 4

At this area, three load buses – Bus 3, Bus 18 and Bus 25 are monitored. It can be seen that the voltages are within the limits. This area has two generators which also operate at a constant speed. The results for the Area C are obtained as shown in Fig. 9. In this case, the Area C is modeled in rack 4. Rack 4 also hosts the second part of the Area D. In this second part the voltage of Bus 23 is 1.05pu. The values of the voltages of all 5 buses monitored in the Area C, rack 4 are in the limits. In conclusion, the load flow results show that no voltage violation and the system remained stable. The system is balanced because the generation power meets the load demand and all bus terminals are within the limits. Therefore, the whole system is stable during the initial conditions. With the above, the base case was established for the 39 bus system and the next step is to develop credible load contingencies through which the voltage stability of the system is analysed.

V.2. Increase of Load Demand Case Study

The IEEE 39 bus system has 19 dynamic loads, and in this case, these loads need to be increased until the load bus voltages drop below the limit of 0.95.

For the loadability studies, the loads have to be automatically gradually increased until the power network reaches its maximum limits of the power margin. As the loads are determined by the active and reactive powers according to the PV and QV curves, it is necessary to design a controller which to be used in the RSCAD software to be capable to change these values. For the RTDS/RSCAD under the draft module, there are two methods that can be used to achieve loadability. The first method uses a slider model in the draft module and under the RSCAD/Runtime module this slider appears and allows the user to control PL and QL values of the loads individually. This is problematic when the system consists of a large number of loads which have to be controlled all at the same time. For this case study 19 loads need to be controlled simultaneously and synchronically. Therefore, method one is not possible to be used. The second method is based on a concept that all 19 loads need a single controller that is able to control the PL and QL set of values. This method uses a scheduler model from the RSCAD library. On the basis of the second method a special controller is developed in this study. The structure of the proposed controller is given in Fig. 10 for the load 3.

This controller is used for all other loads. The scheduler has schedule data source at its input. This schedule data source consists of three functions, namely List, File, and Random. The List function is made up of 30 pairs of schedule data that can be entered. These data are predefined and are set to be sent to the output of the scheduler at a predefined time. In this case, the output is defined as PL and QL. The File function consists of 8000 data pairs of PL and QL powers that are read from a file that stores all predefine data. In this case, the file with data needs to be saved in the same directory as the draft model and it should not have the filename extension. The Random function also has 8000 power data pairs which are generated randomly using Gaussian distribution method.

A new algorithm for controlling the load demand using the scheduler in Fig. 10 is proposed to develop and perform the loadability case study in RTDS/RSCAD environment. In order to be capable to change gradually the load in RSCAD under the draft module the scheduler based controller was configured in order to assist with the load scaling loadability algorithm. The procedure to develop this algorithm is based on the following steps: 1) the load models used are set to a dynamic adjustment.

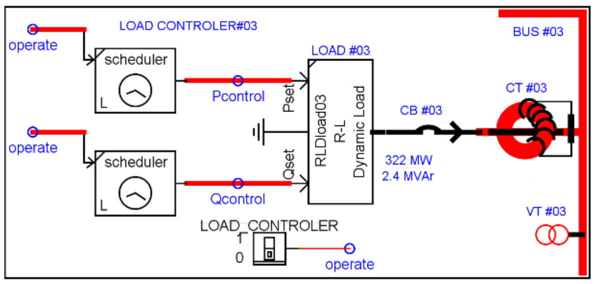


Fig. 10. RSCAD draft module load 3 Power controller configuration

This is done for both the active and reactive powers. In order to achieve this, the load controller for the PL and QL is changed from a slider setting to a compile controller mode. 2) When this mode is selected, the P and the Q set points which are the default values on the loads during normal conditions are provided to the Pset and the Qset control input wires as shown in Fig. 11. During the initial condition, the load 3 consumed the real power of 322MW and reactive power of 2.4 MVar respectively. In this case study, the List function is selected for controlling the PL and QL parameters of the dynamic loads. This experiment is implemented in real-time using RTDS. Under the List configuration window of the schedule component, the load alterations were set to increase by 1% at every second.

During this process, the load buses are constantly monitored. This procedure is based on the initial schedule component sending a new output signal that is used to change the dynamic load. In this case, a start/stop input to the scheduler component is required in the draft module, so that in the runtime module a pushbutton can be used to initiate the loadability signal.

V.3. Determination of the Voltage Stability Margin

The algorithm shown in Fig. 11 is implemented in all 19 loads and the enabling signals were linked by mean of a wire label name, which is used to attach all signals to the main control input in Fig. 10. Once the above is completed the next task is to compile the network under the draft module and monitor the results on the runtime module.

The results showed that when the total load demand is increased by 27% the system is close to its maximum load limit.

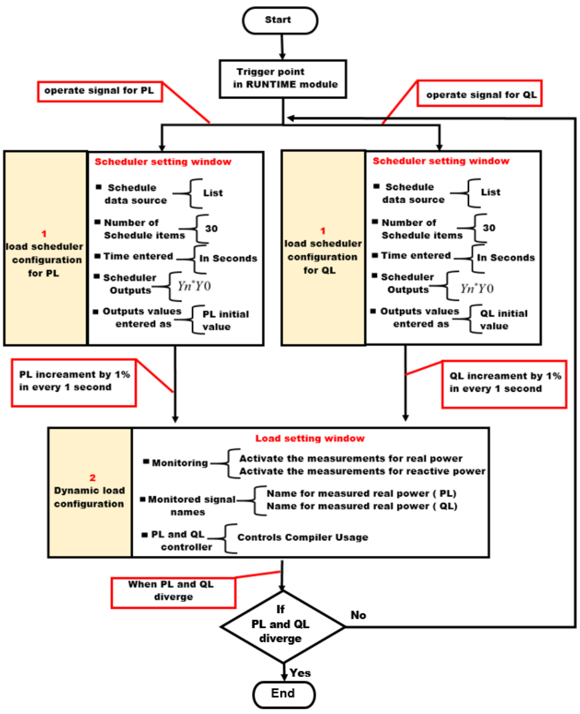


Fig. 11. Algorithm for controlling the load demand

It can be noted that all results from the RTDS racks 1 up to 4 are recorded. Fig. 12 shows only the initial and the increased with 27% values of the active and reactive powers of the load 3 in Area A which is hosted by the RTDS rack 3.

It can be seen that using the algorithm in Fig. 11 the PL3 power is increased from 322 MW to 409.0 MW and QL3 power is increased from 2.4 Mvar to 3.049 Mvar respectively. Fig. 13 presents the load flow results for the Area A in RTDS rack 3 for the case of 27% overloading.

The results also show that the activation of the load scheduler was successful as all loads were increased simultaneously.

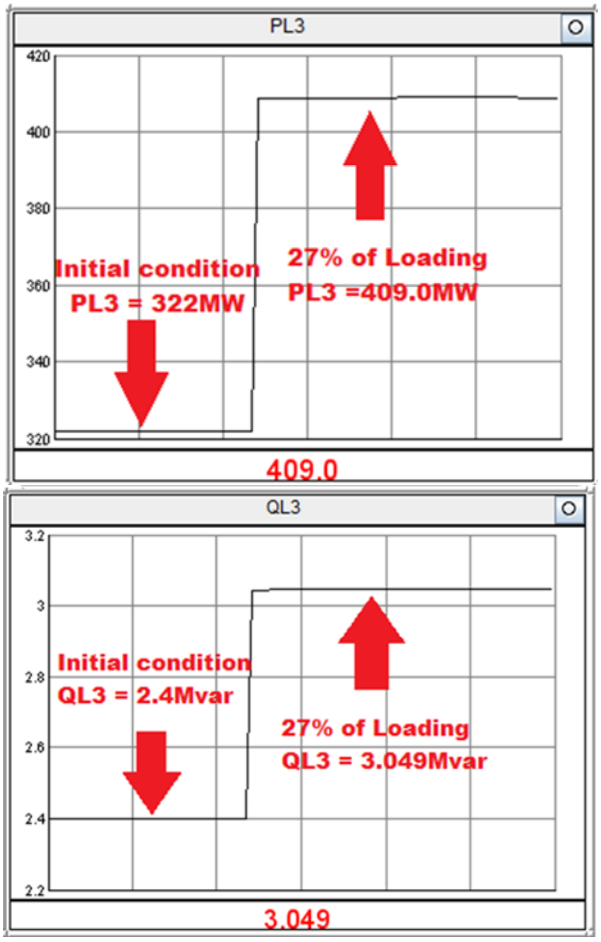


Fig. 12. PL3 and QL3 demands of the load 3 during a normal condition and after 27% loading

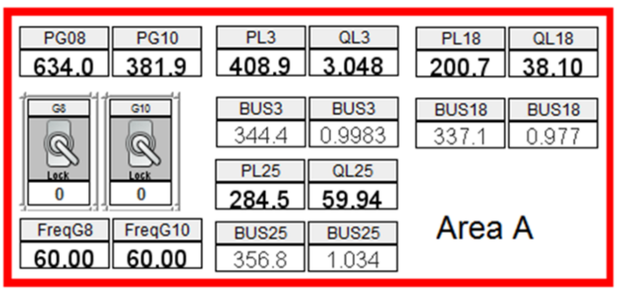


Fig. 13. Load flow results obtained at Area for all three loads during 27% loading of the power network

It can be seen that PL18 and QL18 at bus 18 increased from 158.0 MW to 200.7 MW and from 30.0 Mvar to 38.10 Mvar respectively. For the Bus 25 in the Area A, the real and the reactive powers also increase from 224.0 MW to 284.5 MW and from 47.2 Mvar to 59. 94 Mvar. At the same time, all voltages at the buses are still within the limits after 27% loading and the system is stable.

Fig. 14 shows the results of the whole interconnected system when it is loaded with 27% more demand. At this point, it can be seen that the generation side is still able to supply the load demand. The total power demand increases from 6070.1 MW to 7710 MW and the total reactive power increases from 1683 Mvar to 2138 Mvar without creating an unstable condition. On the basis of the voltage analysis, it is found that the most affected part of the network appears to be Area D which is modeled in RTDS rack 2.

In this case, the lowest bus voltage is at the Bus 24 in area C which drops to 0.9458 pu, followed by the Bus15 voltage which drops to 0.9483 pu and the voltage of the Bus 20 which also dropped to 0.9496 pu. Although the voltages of these buses dropped below the minimum voltage limit they did not affect the power system stability but the system is now close to the maximum loadability margin. Although the system was heavily loaded at this point it still has a good chance to return to voltage stability.

The next task is to continue to increase the load until the system collapses. In order to achieve this, the loads of the whole interconnected system are increased until the load flow diverges. Fig. 15 shows results obtained in Area A when the loads are increased from their initial condition by up to 46%. It can be seen that PL3 and QL3 initial loads are 322 MW and 2.4 Mvar respectively. After 46% loading the real and reactive powers increased to 471.5 MW and 3.14 Mvar respectively.

During the experiment load buses in the system are monitored. For simplicity, the results for Area A are presented. The voltage of the Bus 3 drops to 0.9101 per unit as shown in Fig. 16. This voltage drops below the minimum voltage limits. The same contingency occurs in Bus 18 and therefore the voltage profile of the system is completely violated and the system is at a collapsed state.

The next step is to monitor the whole system during the overloading by 46%. It is observed that the Area D modeled in rack 2 as shown in Fig. 17 is the most vulnerable area when compared to the Area A, Area B and Area C.

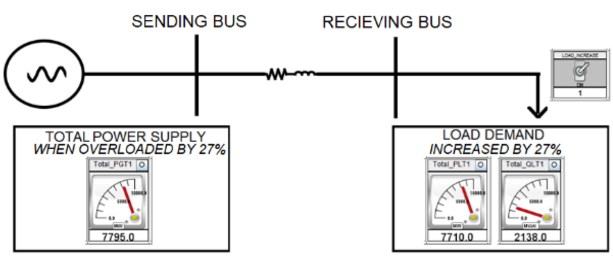


Fig. 14. Load flow results obtained in the runtime of the whole system when it is overloaded by 27%

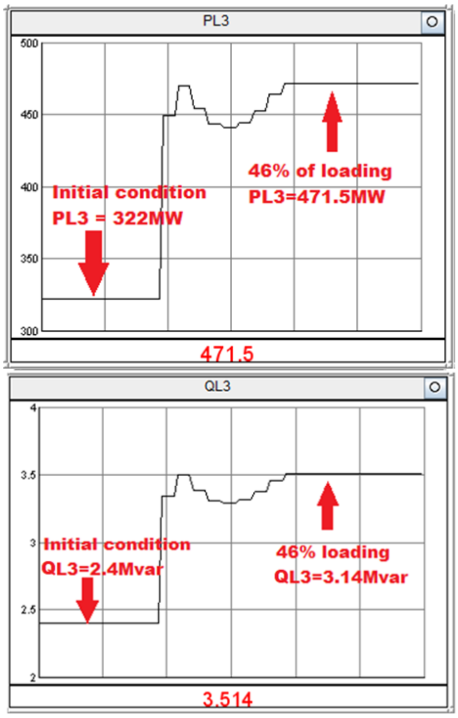


Fig. 15. PL3 and QL3 demands of load 3 during a normal condition and after 46% overloading

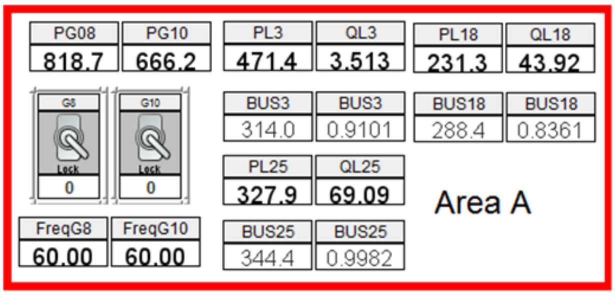


Fig. 16. Load flow results obtained at the Area A for all three loads during 46% overloading of the power network

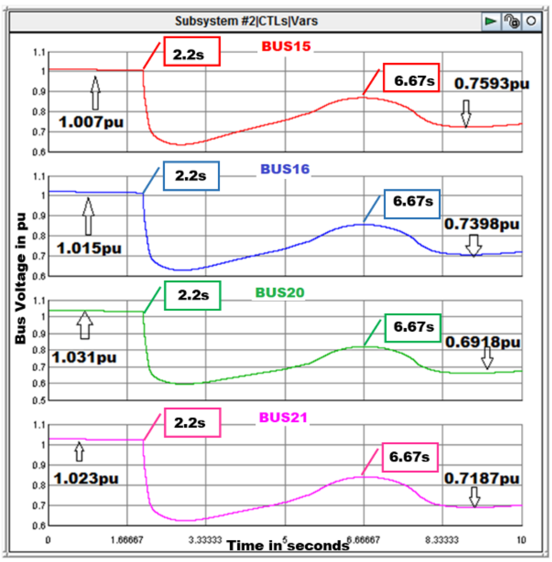


Fig. 17. Load bus voltages behavior at the Area D when the system is overloaded gradually by 46%

The results show that when the system is overloaded by 46% the voltage drops below the limits. The generator voltage regulators are then triggered and the voltages increase a little but the regulators are not efficient enough to maintain it. After some time, the voltage decreases again. The behavior of the voltages in all load buses of the 4-area system is similar. The first critical point is determined by increasing the loads until the system reaches its maximum load margin. This point is found to be at 27% increase of the total loads and it gives an idea of to how much the loads can be increased before the system collapses. It is critical to know this point so that when a protection scheme is implemented the maximum limit is known.

The other critical point is this in which the load flow diverges, meaning the system can no longer recover its stability. This point is found to be when the total system load is increased by 46%. It can be seen that the network was brought to a collapsed state. It must be said that at this point all other means to stabilize the network are assumed to be implemented. Therefore, the last resort that needs to be implemented is the Under-Voltage Load shedding scheme. Under voltage soft Intelligent Electronic Devices (IEDs) are developed to implement the under-voltage load shedding in real-time. The concept that is adopted is based on the decentralized implementation of the UVLS scheme.

The IEDs are installed in all load buses. In order to avoid repetition in this paper, only one load bus configuration of the IED for the load bus is explained in detail. However, the other IEDs configurations are the same. The soft IEDs used are from the RSCAD software module. An algorithm is developed to implement the protection logic of the soft IEDs.

VI. Development and Implementation of the UVLS Scheme

VI.1. The UVLS Logic Scheme Implementation Using Soft IEDs in RTDS Software Environment

Traditionally the existing schemes start shedding a bulk amount of loads at the location in order to stabilize the system. The proposed adaptive load shedding scheme does not operate in the traditional manner. The method developed for the adaptive load shedding scheme is based on distributing the load to be shed among the whole network. This is done by means of first discovering the total percentage of loads that need to be shed and second, distribution of this percentage to be shed equally among all individual loads based on their prioritization. The load prioritization is pre-defined for the participating loads.

The developed control scheme is shown in Fig. 18. The setpoint value of the voltage for the load shedding is defined as 0.95 pu. This value is constantly evaluated.

This setpoint is continuously compared with the measured voltages at the load buses. When the magnitude of the measured voltage of the load bus is lower than the setpoint value, the difference is then sent to the controller.

The controller calculates the volume of the disturbances (overload or increase in load demand) and sends the required data (trip signal) to the actuator (IED) to take the action in the power system network (such as tripping the breaker and shedding the loads). Once this is completed a feedback signal (from the breaker that is open) is sent to be compared with the setpoint input and the next control action is implemented. This control system works until the process variable is equal to the setpoint value.

Shedding of the required loads is implemented in stages in order to avoid over shedding. The configuration of the installed IEDs is based on comparison of the minimum measured phase voltage to the selected threshold voltage. The voltage thresholds setting points are configured for the different stages of the load shedding.

The first stage is normally set to 95% of the normal voltage with some time delay between 0 to 1 second. (it is the time taken by the process to analyze the disturbance and then to make a decision). In this case, since the considered network is for high voltage, the first level is set for 95% of the normal voltage. The second stage is normally set to 93% of the normal voltage with a time delay and the third stage is set to 90% of the normal voltage with a time delay as well. The proposed block diagram controller used for the UVLS scheme implementation as a soft IED in the RSCAD environment is shown in Fig. 19(a). The proposed under voltage load shedding algorithm in Fig. 19(b) is constructed with three sets of RSCAD function block components, namely the comparator function block also known as *IF-THEN-ELSE*, the *Pick-up and drop off* timer and the *Logic SR flip-flop*. In this case, three sets of the comparator function blocks are used where each has two inputs which are represented as A and B respectively. The inputs for the first comparator function block are defined as *VT_OUT* for the signal connected to the input B of the comparator and a floating-point constant is connected to the input signal A of the comparator. In this case, the floating-point constant is programmed to operate for the reference voltage of the stage 1. The *VT_OUT* signal is controlled by the inputs measurements that come from the Voltages Transformers (VTs). The function of the first comparator block is to constantly measure the two input signals and compare them. In a case where input A is equal to or less than the input B, the output of the comparator produces an output Y as high value which is represented by a number one. This case occurs when the load bus voltage drops due to overloading. During the normal operation of the power network, the input B of the comparator must be higher than the input A and therefore the output Y of the comparator function block stays low, which is represented by a number zero.

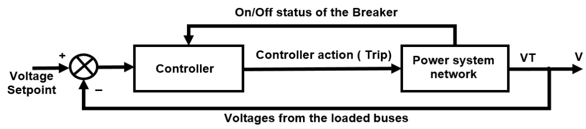


Fig. 18. Closed loop control scheme installed on all load buses

The output Y of the comparator function block is connected to the *Pick-up and off* timer function block, where the delay time is defined. The reason for the time delay introduction is that the signal Y coming from the comparator has no time delay and will instantaneously enable the START signal of the IED.

Once the time delay is introduced, an output signal is produced by the *Pick-up and off* timer function block and is sent to the input of the *Logic SR flip-flop* to trip the loads that are required to be shed for the stage 1. After the stage 1 has operated and the system is still unstable, the stage 2 is then triggered and the same procedure as in stage 1 is followed. The only difference is the value of the signal connected to the input A of the comparator is changed.

The common point of the three-stage comparator function block is the input that comes from the VTs which are connected to the input B. If the voltages from the load buses are lower than the predefined voltage, the comparator will produce a true signal to trip the breaker and shed the required amount of loads. The described above algorithm is implemented in the soft IEDs in the RSCAD environment for every one of the loads. The proposed new scheme of the load shedding controller has three additional components that create flexibility when compared to the traditional schemes as it allows to select the proper amount of load to be shed. Summing junction together with a Selector function and Lookup table function blocks are developed to modify the under-voltage load shedding logic.

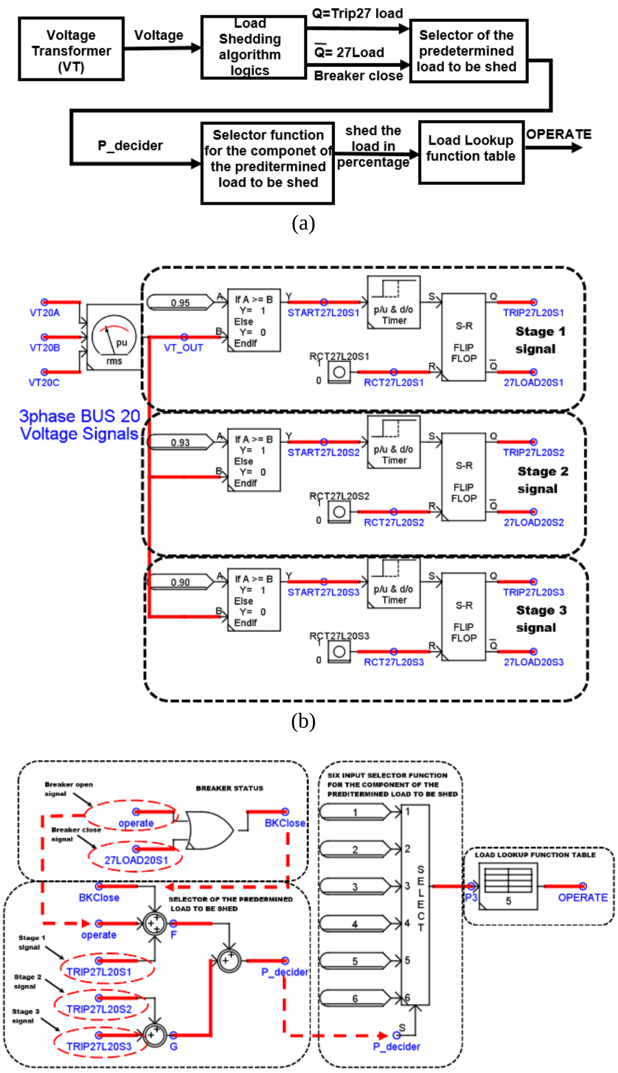
The controller operates in such a manner that when the input signal B is <= from the input signal A for all three stages in Fig. 19(b) the output signals TRIP27L20S1, TRIP27L20S2, and TRIP27L20S3 of the S-R FLIP-FLOP function blocks are sent to the selector of the predetermined loads to be shed as shown in Fig. 19(c).

It calculates and selects an ideal combination of loads that need to be shed and sends the output signal P_decider to the Selector of the predetermined load to be shed function block. This function block converts the integers to real values and selects the persentage of loads that are to be shed in the Lookup table function block. The output signal OPERATE is then send to shed the individual loads at their different locations. The integration of the developed logic algorithm from Fig. 19(b) with the Selectors of the load to be shed forms the logic controller from Fig. 18. The closed-loop system in Fig. 18 performs the UVLS function of the soft IEDs in the software environment of RSCAD.

VI.2. Implementation of the UVLS Scheme

In order to implement the UVLS scheme, the IEDs that are installed in all load buses in the system have to be configured. The under voltage load shedding logic was developed on the draft module of the RSCAD. The Runtime module was used in order to have full control of the logic.

Fig. 20 shows the initial condition for the logic controller before the case study is implemented.



Figs. 19. (a) The proposed block diagram of the controller used for UVLS scheme implementation as a soft IED in the RSCAD environment, (b) Logic block diagram of the developed load-shedding algorithm installed on all load buses in the IEEE 39bus system, (c) Load-shedding logic controller installed on all load buses for decision-making

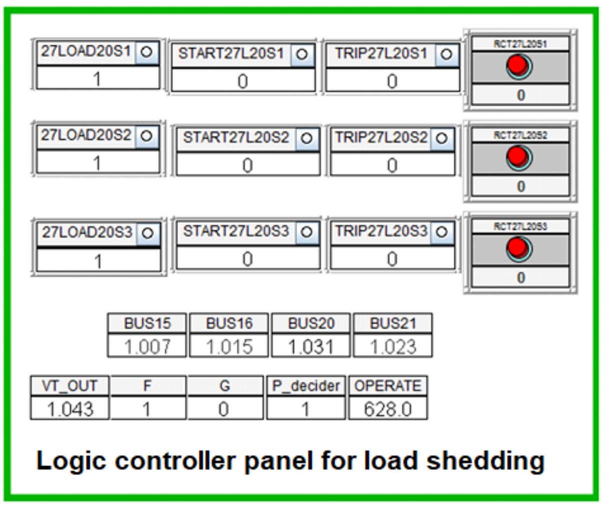


Fig. 20. Logic controller panel for load shedding

The logic controller developed for the UVLS scheme presents information for the initial condition before any disturbance occurs. The controller panel for Bus 20 load is explained in detail. The meters called 27LOAD20S1, 27LOAD20S2, 27LOAD20S3 in Fig. 20 present the signals that control the breakers connected to the dynamic loads in the system for the three stages of the load shedding. When the meters display 1 the breakers are closed and the loads are connected to the system. At the initial condition, the meters have to be at 0 which means that there is no signal that is sent to operate the breakers. In each stage, there are two elements that are conceded namely START and TRIP. The two elements are named START27L20S1, START27L20S2, START27L20S3 for START and TRIP27L20S1, TRIP27L20S2, and TRIP27L20S3 for TRIP respectively. The algorithm uses push buttons RCT27L20S1, RCT27L20S2, and RCT27L20S3 for controlling and resetting the UVLS logic to be true for the initial condition. The case study implemented at this stage has to perform overloading from 28% up to 46%. When the system is operated with 46% overloading the total load demand is increased up to 8886 MW and this point is considered to be the worst one in the power system operation. The load event of increasing the load demand is introduced after 2.2 seconds during the normal condition with an aim to trigger the UVLS scheme and reduce the load demand so that the power system could return back to the initial loading. The panel of the logic controller shows that this operation was successful as displayed in Fig. 21. The results show that the Area D is mostly affected because the load bus voltages for Bus 15, Bus 16, Bus 20, and Bus 21 are all below the minimum voltage limit of 0.95pu as it can be seen in Fig. 22.

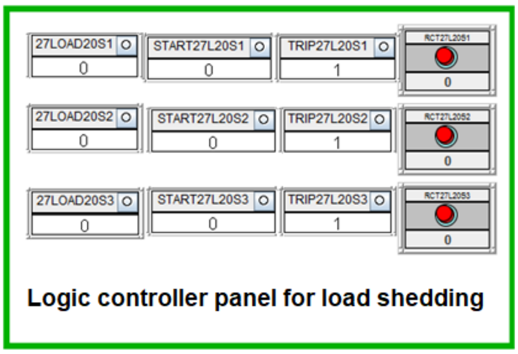


Fig. 21. TRIP signals results of the logic controller used for UVLS operation

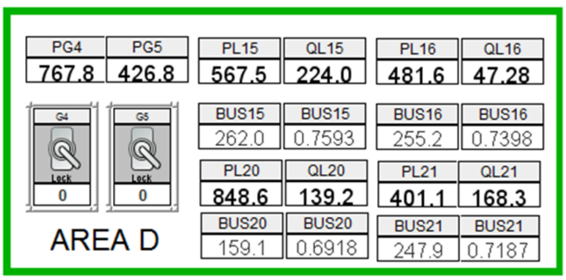


Fig. 22. Load flow results obtained in Area D when the system was overloaded by 46%

Fig. 23 presents the dynamic behavior of the load voltages for Bus15, Bus 16, Bus20 and Bus21 during the process of load shedding. It can be observed that the scheme operated successfully as the mostly affected load buses are recovered back to their initial values. All three stages of the UVLS contributed to this behaviour by shedding 46% of the load. Dynamic behaviour of the bus voltages shows that these voltages drop drastically 2.2 seconds after the overloading occurs. When the load shedding is triggered the load bus voltages start to rise immediately and after few seconds manage to recover to the initial conditions.

The implementation of the proposed UVLS logic controller is successful.

VII. Discussion of the Results from the Real-Time RTDS Simulation

The real-time simulations case studies integrate the performance of the controller for gradually load increase, the multi-stage decision making logic algorithms and the load shedding logic controllers for the decentralized Under Voltage Load Shedding implemented for every load in the multi-area power system. The algorithms and the controllers run without any errors and according to the expectations. The results from the process of creation the load contingences correspond exactly to the requirements of the P-V curve of the considered power network. When the system is overloaded by 46%, the voltage drops below the limits. The generator voltage regulators cannot increase the voltage level enough and after short time, the voltages decrease again. The behavior of the voltage in all load buses of the multi-area system is similar. The multi stage decision making logic algorithm determines the total amount of load to be shed from the balance of the total produced active power by the generators and the load demand.

The obtained results show that the multi stage algorithm works exactly according to the determined set points for the load voltages.

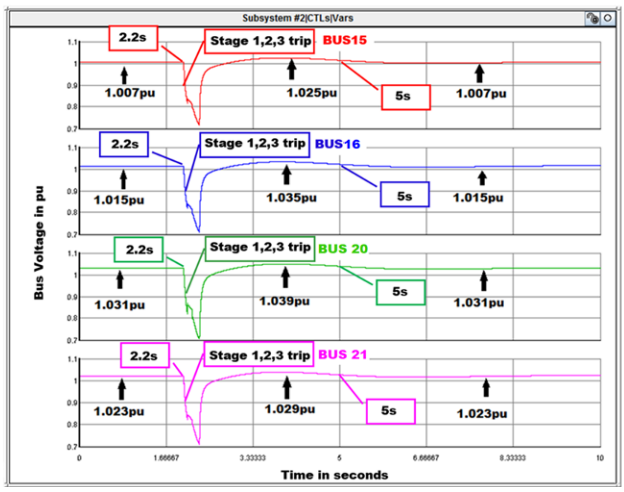


Fig. 23. Load bus voltages in the Area D after the UVLS scheme operation

The load voltages steadily rise with every stage of the algorithm and at the end of the third stage recover to their values before the load contingency. These experiments show that the developed load shedding scheme adjusts well to the magnitude of the disturbances. When the voltage instability occurred, the logic algorithm of the UVLS scheme immediately start implementing the proposed 3 stages of load shedding. The results obtained provided a better understanding and allow deep analysis of the UVLS scheme. It can be concluded that the developed logic controller in the soft IEDs work successfully in real-time. It is also important to note that when the loads are shed in three stages, the condition of overvoltage is addressed. During load shedding the voltage gradually increases and does not reach the upper limit of 1.05pu. This is a good achievement as over load shedding is not possible with the proposed load shedding logic controller. The load bus voltages are able to stabilize in a shorter time in comparison with the time used for implementation of only one stage load shedding. The proposed algorithm speeds-up the operation of the UVLS scheme.

Comparison of the developed in the paper algorithms for development and implementation of UVLS scheme with different state of the art optimization-based, index-based, adaptation-based and protection equipment-based algorithms and methods leads to the conclusion that the algorithms based on optimization (also for the cases of indexes and adaptation) are not created and developed for real-time implementation as they are:

- Computationally complex and need long time to complete the calculations;
- Consider only one criterion to be optimized;
- Most of them develop algorithms to minimize the load to be shed, which requires a lot of time for calculations too;
- Algorithms are capable to reach only local optimum and propose a solution for a part of the system. It is necessary to repeat the algorithm for the various parts of the network, which requires long time;
- The decisions are not obtained in real-time. Load shedding plans are normally generated through static simulation in advance and can be used for certain load conditions in the network. The results from their application are not adequate to the current behavior of the system;
- The load shedding is implemented as one stage procedure which leads to possibilities for over or under load shedding creating conditions for under or over voltages.

On the basis of the above it can be said that the optimization-based, indexes-based and adaptation-based algorithms for load shedding are slow, cannot reduce the losses of the network in real-time, they are not sensitive and accurate according to the real-time behavior of the power network, and are not reliable and flexible for real-time application as the decisions are taken not in real-time and do not depend on the configuration, type, voltage level and structure of the network.

VIII. Conclusion

This paper focuses on the development of an multi-stage adaptive closed loop UVLS scheme for multi-area power networks. It is based on the new UVLS logic controller developed in RSCAD software environment. The logics are implemented as a protection mechanism and implemented as under voltage elements in the RSCAD soft IEDs. The IEEE 39 bus system is considered as a case study and modeled in the draft RTDS module of the RSCAD software. This case study uses the developed loadability procedure to test the proposed logic controller. The developed multi stage adaptive load shedding algorithms and controllers contribute to the growth of knowledge and real-time implementation of the UVLS schemes in single and multi-area power networks.

These algorithms and methods optimize the closed loop load shedding scheme in relation to:

- Minimum time for implementation in real-time conditions based on the adaptation to the load conditions and the continuous monitoring of the network behavior;
- Minimum economic losses and reliability increase in the power system operation because of the real-time system monitoring and the fast operation of the controllers;
- High sensitivity and accuracy of the algorithms and controllers towards the loads and generators behavior changes resulted in the exact amount, type and sequence of load to be shed and a protection against the under or over load shedding;
- Flexibility according to the type, configuration, voltage level and structure of the power network due to the building principle of these algorithms and methods being the P-V curve operational characteristics of the power network and the balance between the generation and load in real time. Only real-time operational data for power and voltage are necessary for implementation of the algorithms. This fact makes the proposed scheme wide applicable.

Another type of contribution is towards the development of new models and software for extension of the RSCAD software environment, as follows:

- The UVLS logic of the soft IEDs is developed and operated successfully in the framework of RSCAD software. The soft IEDs also brought an extension to the RSCAD IED models in the RTDS library in terms of capability to do load shedding in stages;
- The developments in this paper extended the capability of the RSCAD software to be used for more advanced power stabilities studies;
- The existing software environment of RSCAD could only operate for one stage of the load shedding. It is dangerous to just operate using one stage. It might lead to under or over shedding which may cause other problems in the power systems. Therefore, the developed soft IEDs for UVLS schemes brought a safer, reliable, and flexible solution for the RSCAD/RTDS real-time environment.

The further developments of the proposed multi-stage adaptive load shedding scheme will be in the following directions: centralized implementation, development of new adaptive controllers for the case of integration of the Distributed Energy Resources to the multi-area power network, and development of a methodology and controllers to achieve balance between reserve utilization and load shedding in the case of generators contingencies.

From real-time implementation point of view, the soft Intelligent Electronic Devices will be substituted by Industrial grade IEDs and the developed schemes will be built for Hardware in the Loop with RTDS real-time simulation.

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References

[1] P. Kundur, G.J. Rogers, D.Y. Wong, L. Wang, M.G. Lauby, A comprehensive computer program package for small signal stability analysis of power systems, *Electrical and Electronics Engineers (IEEE), Transactions on Power Systems*, vol. 5, n. 4, November 1990, pp. 1076-1093.

[2] D. Hazarika, A.K Sinha, Method for optimal load shedding in case of generation deficiency in a power system, *Electrical Power & Energy Systems (EPEES)*, vol. 20, n.6, August 1998, pp. 411-420.

[3] A. Maiorano; R. Sbrizzai; F. Torelli; M. Trovato, Intelligent load shedding schemes for industrial customers with cogeneration facilities, *International Conference in Power Engineering Society*, 31 Jan.-4 Feb. 1999 Winter Meeting, IEEE. vol.2, pp. 925–930.

[4] D. Xu, A.A. Girgis, Optimal load shedding strategy in power systems with distributed generation, *Electrical and Electronics Engineers (IEEE)*, vol.2. pp. 788–793.

[5] Z, Ding, D.A. Carts, S. Srivastava, New load shedding scheme for islanded power systems, *International Conference on System of Systems Engineering on Institute of Electrical and Electronics Engineers/System, Man, and Cybernetics (IEEE/SMC)*, 24-26 April 2006, pp.167-172.

[6] X. Fu, X. Wang, Load Shedding Scheme Ensuring Voltage Stability, In Power Engineering Society General Meeting, *Institute of Electrical and Electronics Engineers (IEEE)*, 24-28 June 2007, pp. 1–6.

[7] N. Tatbul, U. Cetintemel, S. Zdonik, Efficient Load Shedding Techniques for Distributed Stream Processing, *The 33rd international conference on Very large data bases*, Vienna, Austria, 23-28 September, 2007, pp. 159-170.

[8] R. Faranda, A. Pievatolo, E. Tironi, E, Load Shedding: A New Proposal, *Electrical and Electronics Engineers (IEEE) Transactions on Power systems, vol. 22, n. 4,* November. 2007, pp.2086–2093.

[9] M. Nizam, A. Mohamed, A. Hussain, An Adaptive Undervoltage Load Shedding Against Voltage Collapse Based Power Transfer Stability Index, *Journal of Electrical Engineering & Technology (JEET)*, vol. 2, n. 4, January 2007, pp. 420-427.

[10] V. Chin, Z. Y. Dong, T. K. Saha, J. Ford, J. Zhang, Adaptive and optimal under frequency load shedding, *Australasian Universities Power Engineering Conference (AUPEC)*, 14-17 Dec. 2008, pp. 1–6.

[11] R. A. Zahidi; I. Z. Abidin; H. Hashim; Y. R Omar; N. Ahmad; A. M. Ali, Study of Static Voltage Stability Index as an Indicator for Under-Voltage Load Shedding Schemes, The 3rd *International Conference on Energy and Environment(ICEE)*, 7-8 Dec. 2009, pp.256–261.

[12] S. Koch, S. Chatzivasileiadis, M. Vrakopoulou, G. Andersson, Mitigation of cascading failures by real-time controlled islanding and graceful load shedding, *In Bulk Power System Dynamics and Control (iREP)*, 1-6 Aug. 2010, pp. 1-9.

[13] B. Charoenphan, K. Audomvongseree, Optimal load shedding scheme under contingency condition considering voltage stability problem, *In Electrical Engineering/ Electronics Computer Telecommunications and Information Technology (ECTI-CON)*, 19-21 May 2010, pp. 1006–1010.

[14] E. J. Coster, J.M.A. Myrzik, B. Kruimer, W.L. Kling, Integration Issues of Distributed Generation in Distribution Grids, *Electrical and Electronics Engineers (IEEE)*, vol. 99, Issue: 1, January, 2011, pp.28–39.

[15] D. Rudrapal, S. Das, A Pandey, N. Kar, Automated Load Shedding Period Control System, *International Journal on Computer Science and Engineering (IJCSE)*, vol. 3 n. 5, May 201, pp. 1764-1772.

[16] T. Amraee, A.M Ranjbar, R. Feuillet, Adaptive under-voltage load shedding scheme using model predictive control, *Electric Power Systems Research*, vol 81, n.7, July 2011, pp. 1507-1513.

[17] N. A. Yusof; H. Mokhlis; M. Karimi; J. A. Laghari; H. A. Illias; N. M. Sapori, Under-voltage load shedding scheme based on voltage stability index for the distribution network. The *3rd IET International Conference on Clean Energy and Technology (CEAT)*, 24-26 Nov. 2014, pp. 1-5.

[18] A. Arief, Under Voltage Load Shedding Using Trajectory Sensitivity Analysis Considering Dynamic Loads, *Universal Journal of Electrical and Electronic Engineering (UJEEE)*, 2014, pp.118–123.

[19] P. Kundur, *Power system stability and control*, N. J. Balu & M. G. Lauby, eds., New York San Francisco (McGraw Hill, Inc., 1994).

[20] V. Converti; D.P. Gelopulos; M. Housley; G. Steinbrenner, Long-term stability solution of interconnected power systems, *Electrical and Electronics Engineers (IEEE) Transactions on Power Apparatus and Systems*, vol.95, n.1, January. 1976, pp. 96-104.

[21] C. Tayler, *Power system Voltage Stability*, New York (McGraw Hill, Inc, 1994).

[22] M.A. Pai, *Energy Function Analysis for Power System Stability*, (Boston: Kluwer Academic Publishers, 1989).

[23] *RTDS manual*, (RTDS Technologies Inc., 2014).

[24] I. Kaffashan, T. Amraee, Probabilistic undervoltage load shedding using point estimate method, *Institution of Engineering and Technology (IET), Transmission Distribution*, vol. 9, n.15, November 2015, pp. 2234-2244.

[25] T. Shekari, A. Gholami, F. Aminifar, M. Sanaye-Pasand, An Adaptive Wide-Area Load Shedding Scheme Incorporating Power System Real-Time Limitations, *Electrical and Electronics Engineers (IEEE), Systems Journal*, vol.12, n.1, March 2018, pp.759-767.

[26] B. Hoseinzadeh, F.M.F. Silva, C.L. da Bak, Adaptive Tuning of Frequency Thresholds Using Voltage Drop Data in Decentralized Load Shedding, *Electrical and Electronics Engineers (IEEE), Transactions on Power Systems*, vol.30, n.4, July 2015, pp. 2055-2062.

[27] I. Kaffashan, S.H. Mortezaee, T. Amraee, A robust Undervoltage load shedding scheme against voltage instability, *Turkish Journal of Electrical Engineering and Computer Sciences (TJEECS)*, 15 April 2016, pp. 3309-3320.

[28] A.C. Adewole, R. Tzoneva, A. Apostolov, Adaptive under-voltage load shedding scheme for large interconnected smart grids based on wide-area synchrophasor measurements, *Institution of Engineering and Technology* (*IET*) *Generation, Transmission Distribution*, vol. 10, n. 8, 19 May 2016, pp. 1957-1968.

[29] A. Mahari, H. Seyedi, A wide area synchrophasor-based load shedding scheme to prevent voltage collapse, *International Journal of Electrical Power & Energy Systems (IJEPES)*, vol 78, June 2016, pp. 248-257.

[30] M. Derafshian, N. Amjady, S. Dehghan, Special protection scheme against voltage collapse, *Institution of Engineering and Technology (IET)*, vol. 10, n. 2, 16 November 2016, pp. 341-351.

[31] B. Nadai Nascimento, A.C.Z. de, Souza, J.G. de, Carvalho Costa, M. Castilla, Load shedding scheme with under-frequency and under voltage corrective actions to supply high priority loads in

islanded microgrids, *Institution of Engineering and Technology (IET), Renewable Power Generation*, vol.13, n.11, 13 June 2019, pp 1981-1989.
[32] N.M. Sapari, H. Mokhlis, J.A. Laghari, A.H.A. Bakar, M.R.M. Dahalan, Application of load shedding schemes for distribution network connected with distributed generation: A review, *Renewable and Sustainable Energy Reviews (RSER)*, vol. 82, n.1, February 2018, pp. 858-867.
[33] M. Javadi, T. Amraee, The mixed-integer linear formulation for undervoltage load shedding to provide voltage stability, *Institution of Engineering and Technology (IET)*, vol 12, n. 9, 3 May 2018, pp 2095-2104.
[34] M. Choobineh, D. Silva-Ortiz, S. Mohaghegh, An Automation Scheme for Emergency Operation of a Multi-Microgrid Industrial Park, *Electrical and Electronics Engineers (IEEE), Transactions on Industry Applications*, vol.54, n.6, 28 June 2018, pp. 6450-6459.
[35] K. Narayanan, S.A. Siddiqui, M. Fozdar, Hybrid islanding detection method and priority-based load shedding for distribution networks in the presence of DG units, *Institution of Engineering and Technology (IET), Generation, Transmission Distribution*, vol.11, n.3, 9 February 2017, pp. 586-595.
[36] X. Xu, H. Zhang, C. Li, Y. Liu, W. Li, V. Terzija, Optimization of the Event-Driven Emergency Load-Shedding Considering Transient Security and Stability Constraints, *Electrical and Electronics Engineers (IEEE*), vol. 32, Issue: 4, 31 October 2016, pp. 2581-2592.
[37] J. Mohammadi, F.B. Ajaei, Adaptive Voltage-Based Load Shedding Scheme for the DC Microgrid, *Electrical and Electronics Engineers (IEEE), Access*, vol. 7, 15 August 2019, pp. 106002-106010.
[38] S.M. Hashemi, M. Sanaye-Pasand, M. Abedini, Under-impedance load shedding: a new preventive action against voltage instability, *Institution of Engineering and Technology (IET) Generation, Transmission & Distribution*, vol 13,n.2, January 2019, pp.201-208.
[39] A. Khamis, H. Shareef, A. Mohamed, Islanding detection and load shedding scheme for radial distribution systems integrated with dispersed generations, *Institution of Engineering and Technology (IET) Generation, Transmission & Distribution*, vol 9,n.15, November 2015, pp. 2261-2275.
[40] J. Mohammadi, F.B. Ajaei, DC Microgrid Load Shedding Schemes, *The 55th Industrial and Commercial Power Systems Technical Conference (I&CPS) Electrical and Electronics Engineers (IEEE)*, 5-8 May 2019.
[41] Reyes-Jordan, L., Rios, M., Load Shedding in Power Systems Based on a Fuzzy Logic Decision and Sensibility of Stability Prediction and Fast Voltage Indices, (2016) *International Review of Electrical Engineering (IREE)*, 11 (5), pp. 496-505.
doi: https://doi.org/10.15866/iree.v11i5.10137
[42] Tephiruk, N., Hongesombut, K., Enhancement of Stabilizing Performance of a Microgrid Using Energy Storage System with Under Frequency Relay, (2016) *International Review of Electrical Engineering (IREE)*, 11 (6), pp. 635-643.
doi: https://doi.org/10.15866/iree.v11i6.10342

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