Renuga VERAYIAH [1], Azah MOHAMED[1], Hussain SHAREEF[1] , Izham ZAINAL ABIDIN[2]

Universiti Kebangsaan Malaysia (1), Universiti Tenaga Nasional (2)

Review of Under-voltage Load Shedding Schemes in Power System Operation

***Abstract**. A voltage collapse event is complex and localized in nature, but its effect is extensive. A vital effect of voltage collapse is total system collapse or blackouts, which will result in a significant loss to utility companies. Online monitoring of power system stability has thus become an important factor for electric power utilities. The final resort prevent the occurrence of a voltage collapse incident is the implementation of an under-voltage load shedding (UVLS) scheme. This paper focuses on the introduction of the UVLS scheme and presents an overview of the principles of the UVLS that are crucial to the design of such a protection scheme. This paper also presents the existing industrial practices and other research methods available to date.*

***Streszczenie.** W artykule opisano algorytm UVLS (Under Voltage Shedding Schemes) zastosowany do monitorowania stabilności systemu energetycznego I zapobiegania jego zapaściom. Artykuł jest przeglądem metod stosowanych w praktyce oraz prac badawczych w tej dziedzinie. (**Metody UVLS w zastosowaniu do monitorowania stabilności systemu energetycznego I zapobiegania jego zapaściom**)*

Keywords: voltage stability, voltage collapse, under voltage load shedding.
Słowa kluczowe:

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Introduction

Existing power systems are significantly more susceptible to voltage collapses today than many years ago because such systems are stressed because of the huge power transfers across grids. These transfers cause transmission lines to operate close to their limits. In addition, generation reserves are minimal, and reactive power is often insufficient to satisfy load demands. Thus, power systems have become more vulnerable to disturbances, outages, and instability. The disturbances that occur in power systems include faults, sudden loss of generation, and sudden rise in load demand [1]. All these disturbances vary in intensity and may cause the instability of the power system. For instance, when a sudden large industrial load is switched on, a power system may become unstable. Therefore, the stability state of the system should be studied and predicted to avoid such occurrences.

The worst effect of voltage instability is voltage collapse. Voltage collapse refers to the process by which voltage instability results in the loss of voltage in a significant part of the system, thus causing blackout or total power outage [2]. Over the past two decades, large voltage collapses occurrences have been reported throughout the world each year. Many incidents of real voltage collapses have also been recorded [3- 6].

Three main factors generally cause voltage collapse incidents worldwide. The first factor is transmission system limitation. The major incidents related to transmission system limitations are the 1970 New York Disturbance [6] and the 1979 New Zealand disturbance [3]. In the New York event, an increased loading on the transmission system and the tripping of a 35 MW generator resulted in a post-contingency voltage decline. Meanwhile, the tripping of the only unit in the southern part of New Zealand that produces 270 MW caused a slow voltage decline. Within the next 15 minutes, the voltages declined to 0.75 pu, making the synchronizations of the 70 MW gas turbine impossible. Finally, both the systems were voltage protected by performing manual load shedding.

The second factor is the load behavior, including on-load tap changer performance. The Tokyo incident in July 1987 [7] is a good example of this scenario. The unexpected hot weather triggered the load to pick up at almost 1% per minute, and the unfavorable characteristics of air conditioners contributed to a major voltage collapse.

The influence of protection and control systems is the third factor that contributes to voltage collapse. The collapse in France in 1987 was aggravated by the fact that many generators were tripped by the maximum field current protection relays instead of being field current limited [8]. This condition highlights the importance of considering protection systems in the analysis. This finding also implies the necessity of having a well-tuned control and protection system. The largest power outage in world history that occurred in New Delhi in July 2012 further shows that all aforementioned factors affect the power grid and thus cause its collapse. Multiple factors contributed to this incident. Such factors included as weak interregional power transmission corridors caused by multiple outages, including forced and scheduled outages; high loading on the 400 kV Bina–Gwalior–Agra link, which was eventually lost because of the mis- operation of its protection scheme; and balancing excess generation caused by the load shed [9].

Under-voltage load shedding (UVLS) is specifically designed as a safety measure to prevent widespread voltage collapse in the event of a severe deficit in local or system-wide area reactive power reserves. UVLS has become the preferred strategy of power utilities because it is a cost-effective solution to address voltage stability issues. However, before implementing UVLS, several issues have to be addressed. These issues include the location of load shed, the quantum to shed at the identified locations, and the timing of load shed. These three issues have been addressed by many researchers in developing UVLS schemes [10–14]. Nevertheless, there exists another method besides UVLS, known as reverse action [15], in order to impose the power demand reduction in a critical power system. The voltages at load buses can be reduced using the on- load tap changing transformers. This reverse action mode is justified if a reduction in the voltage is accompanied by a reduction in a reactive power demand.

This paper aims to introduce the UVLS scheme and present an overview of the principles of UVLS that are crucial in designing such protection schemes. Moreover, this paper presents the existing industrial practices that have been developed, as well as the implementation of other available UVLS methods.

Review of Related Literature on Load Shedding

Literature in the web of science database, which is the largest abstract and citation database for research literature and quality web sources, was reviewed. The survey spans the last 13 years from 1994 to 2013. Figure 1 statistically illustrates the number of published research papers on power system load shedding over the past 13 years, with a total of 661 papers.

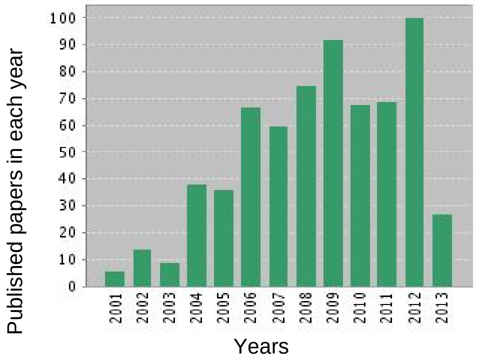

Fig.1. Number of published papers on load shedding in power systems [16]

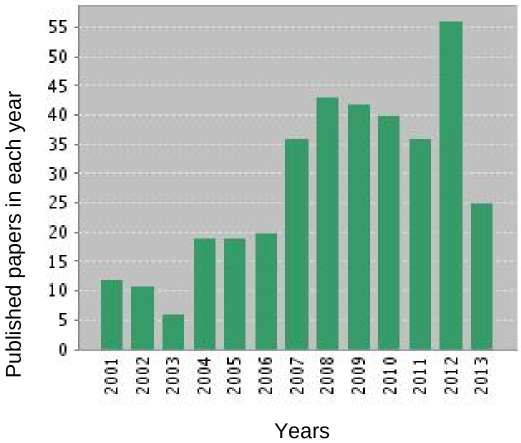

Fig. 2. Number of published papers on load shedding as a method to solve voltage collapse [16]

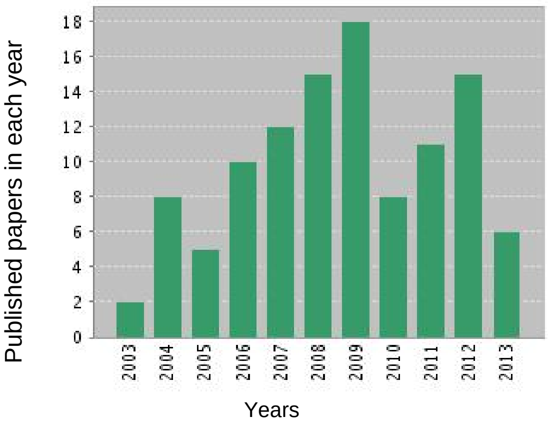

Fig. 3. Number of published papers on the UVLS scheme as protection for voltage collapse [16]

Three hundred sixty-five papers were published with the topics related to load shedding as a method to solve voltage collapse. In addition, the importance of the UVLS scheme as a protection for voltage collapse is evident. As shown in Figure 3, the number of related publications is 110, whereas the number of related research papers showed an increasing trend from 2007. Thus, the UVLS scheme is an important issue in addressing power system stability problems, which is why such methods have recently attracted considerable research interest.

Principles of UVLS

As discussed by many researchers, three main UVLS issues have to be considered, namely, the amount of load for curtailment, the timing to execute load curtailment event, and also the appropriate location for load curtailment [11].

Amount of Load Shed

Tripping appropriate amount of load is a crucial deciding factor in restoring the instability of a power system network. Tripping fewer loads than necessary will not effectively overcome voltage collapse. However, tripping an excessive amount of load may raise a new concern, which is the over frequency condition, because the system will generate load in excess of the load demand.

Load characteristics serve an important function in determining the capability of an unstable power system to regain its stability after the disturbance. Two types of load models that influence the amount of load curtailment are static and dynamic loads. Static loads represent the active and reactive power consumed by the load at a particular instant of time as a function of the bus voltage and frequency at that instant. In steady state power analysis, system frequency is considered constant, such that the power consumed is a function of the bus voltage alone [17]. By contrast, dynamic load models consider the time-varying nature of the operating characteristics of power system components, including induction motors, discharge-type lamps, as well as thermostatically controlled loads, such as air conditioners and under load tap changers [18]. No standard or generic system load model can readily be used by utilities, especially for work related to voltage stability [19]. The Western Electricity Coordinating Council has recommended the representation of 20% of the load as induction motors because the mechanism of voltage instability is dependent on the voltage sensitivity of the non-motor load, as well as on the percentage of motor load.

To overcome these issues, many studies have been developed for determining optimal amount of load to be shed during voltage collapse occurrence. The majority of the methods proposed are aimed at minimizing the load shedding amount.

Reference [19] presents a practical approach to determine the best location and the minimum amount of load to be shed for an event-based load shedding scheme. A non-linear optimization problem is solved by using a multi-stage method. In this work, the non-linear problem is solved stage by stage, and the load shedding amount is limited to a small amount at each stage. Reference [20] proposes the utilization of Genetic Algorithm (GA) technique to optimize the amount of load to be shed. Such technique was implemented in the Hydro–Quebec system. This method yields optimized rules that can easily be implemented and interpreted, but many aspects are yet to be investigated. The algorithm needs to be tuned for it to handle a larger number of scenarios, a wider range of load behavior, and a detailed time simulation for short-term voltage instability problems. Thus, alternative combinatorial optimization methods should be considered. An example is presented in [21], whereby the minimal amount of load shed was determined by a binary or incremental search, resorting to time-domain simulations to check system behavior. As far as long-term voltage stability is concerned, the computing time is dramatically reduced by using a quasi steady- state simulation technique.

In [22], a new minimum load shedding approach is proposed. Using the damped Newton– Raphson method, the system minimum mismatch function is calculated to identify the weakest bus and to determine the most effective load shedding strategy. The minimum load shedding amount is calculated by solving the modified power flow equations, where the weakest bus of voltage minimum mismatch solution is set as a known parameter, and the scaling of the load coefficient of the shedding load bus is the unknown parameter. The desired precision is then obtained by using the traditional PV curve method.

The emergence of intelligence techniques have simulated and assessed the performance of the UVLS scheme. Factors such as deregulation, dispersed generation, continuous load growth, and ever increasing dependence on reliable electricity supply by modern society triggered the development of such intelligent load shedding as a means to preserve system integrity and to provide acceptable system performance. The adaptive and intelligence techniques arising from meta-heuristic algorithms are Particle Swarm Optimization [23], Firefly Algorithm [24], Evolutionary Programming [25], Artificial Neural Network [26], Quantum Inspired Evolutionary Programming [27], GA [28], and Ant Colony Optimization [29]. These techniques have been implemented to solve the key issues of the UVLS scheme, such as the minimum amount of load shed, the location to shed, and the timing of load shedding.

Location for Load Shedding

Small disturbance analysis coupled with dynamic simulations and further enhanced by optimal power flow methodology is among the tools employed in the determination of load shedding location. The load buses are usually categorized in the order of the weakest bus to the strongest bus [20]. Graphically obtained from the PQ curve, the weakest bus tends to have the highest dV/dQ component and tends to be more susceptible to voltage collapse. Consequently, the weakest bus is the most appropriate candidate for load shedding. Comparatively, in [30], each bus was monitored for voltage collapse instead of implementing load shedding at the weakest bus through ranking system application. Once detected, UVLS is activated at a particular bus. The main disadvantage of this approach is that an optimum amount of load is not shed, given that power–voltage characteristics of the lines will change when load shed is activated at one bus.

In [19], aside from determining the minimum amount of load to be shed using a multi-stage approach in non-linear programming, a novel multiport network is proposed to determine the best location for load shedding. Based on the multiport network model, fast ranking of the load locations and generator factors can be conducted with less computational efforts. The results obtained were compared and verified using a well-known modal analysis method. Modal analysis has been used in many studies to compute the critical areas before applying corrective actions related to active and reactive power. A drawback found in the modal analysis is the necessity for evaluating the maximum loading point to obtain an idea of which areas are critical. Such areas are assessed at the base case. In some cases, the reliability of the critical areas is low, especially for the reactive shape in systems with less loading [31].

Significant progress has recently been made in the identification of critical buses by using proximity indices. Reference [32] demonstrated a line stability index known as Fast Voltage Stability Index (FVSI) to determine the maximum load that can possibly be connected to a bus to maintain stability before the system reaches its bifurcation point. This point is determined as the maximum loadability of a particular bus beyond which system instability will occur. The single maximum loadability obtained from the buses will be sorted in ascending order. The highest rank implies a weak bus with low sustainable load, whereas the lowest ranked bus sustains a higher load with greater stability margin. Developed proximity indices similar to FVSI include the line stability index, LMN [33] and line stability index LQP [34]. Another index known as Voltage Instability Proximity Index is presented in [35] to identify the weak location in a power network. The index is defined by estimating Thevenin equivalent parameters using the online power flow technique.

Besides using these indexes, the other approaches used to identify the weak areas or buses differ from one another. Other techniques include singular value decomposition, voltage stability margin index, voltage stability limit, and Kohonen neural network-based method [36- 38]. However, the performance of these indexes shows a high degree of accuracy and reliability for the evaluated system.

Timing for Load Shedding

The timing of load shedding performance should consider the amount of load shed and the location for load shedding. In reality, various system components attempt voltage recovery at different time frames. The minimum amount of time allowed before a UVLS scheme is activated is the time taken from the commencement of voltage collapse. Moreover, the maximum amount of time allowed before a UVLS scheme is triggered is the time taken for all the intervening system components to attempt system recovery.

Research undertaken to compute for the timing of load shedding occurrence involves dynamic simulations. One example is explained in reference [40], in which a test power system with discrete Load Tap Changer (LTC) dynamics is used to calculate the maximum time delay that a system can withstand and from which it can still recover a stable operating condition for a given load-shedding scheme. This method implements a specific predetermined load-shedding scheme and evaluates its successfulness based on whether the stable equilibrium set is reached. Given the initial conditions and the direction of system trajectory, the intersection point of the fault on- trajectory with a specific type of boundary type of region of attraction can be calculated. Thus, the critical load shedding can be computed. Shedding of a more critical bus expectedly yields more desirable results.

Industrial Practice in UVLS

Various types of load shedding techniques have been implemented by power system operators in power networks. Different countries may implement different strategies that can best maintain whole system stability. The basic guideline in designing a UVLS scheme developed by the Technical Studies Subcommittee of Under voltage Load Shedding Task Force of Western Systems Coordinating Council (WSCC) is described below [40]:

i. Load shedding scheme should be designed to coordinate with protective devices and control schemes for momentary voltage dips, sustained faults, low voltages caused by stalled air conditioners, and so on.
ii. Time delay to initiate load dropping should be in seconds, not in cycles. A typical time delay varies between 3 seconds and 10 seconds.
iii. UVLS relays must be on PTs that are connected above automatic LTCs.
iv. Voltage pick-up points for the tripping signal should be set reasonably higher than the “nose point” of the critical P-V or Q-V curve.

v. Voltage pick-up points and the time delays of the local neighboring systems should be checked and coordinated.

vi. Redundancy and adequate intelligence should be built into the scheme to ensure reliable operation and to prevent false tripping.

vii. Sufficient load should be shed to bring voltages to the minimum operating voltage levels or higher. The VAR margin should be maintained according to the Voltage Stability Criteria of the WSCC.

Table 1 shows the categories of UVLS scheme applications in industrial practices.

Conclusion

UVLS scheme is applied as a security measure in situations where voltage collapse is anticipated and can potentially result in total system collapse. This scheme is the last resort in terms of protective counter-measures initiated after exhausting all other methods. To design a UVLS scheme, key concepts associated with voltage stability and UVLS must be understood. A UVLS scheme is usually composed of several stages. Each stage is characterized by voltage threshold, amount of load, and delay before tripping. The objective of an effective UVLS scheme is to curtail a minimum amount of load and to provide a rapid, smooth, and harmless transition of the system from an emergency situation to a normal equilibrium state. This paper provides an introduction to the UVLS scheme and presents a detailed overview of its underlying principles that are crucial in designing such a protection scheme. In addition, this paper presents the existing methods that are developed by researchers to address the issues involved in UVLS, which include the amount of load to shed, the timing of load shedding event and the location of where to load shed. Finally, the industrial practices and strategies being implemented by power industries are summarized.

Table 1. UVLS Schemes Applied in Industries

Classification of Under Voltage Load Shedding Scheme	
Centralized • A centralized scheme has under-voltage relays installed at key system buses within the area, and tripping signals are transmitted to shed load at various locations. These schemes are categorized as SPS or WAPS. • Examples: Hydro–Quebec, Tenaga Nasional Berhad	Decentralized • The relays operate if the voltage decreases to a preset threshold value, similar to the operation of UVLS. • Examples: TEPCO (four zones with microprocessor or based of relay links via ring-structured communication)
Static • The static scheme is used to shed a fixed amount of load at every stage. • Examples: Tenaga Nasional Berhad	Dynamic • The dynamic/adaptive scheme sheds loads, not at a fixed amount (dynamic amount), but depending on the magnitude of disturbance and dynamic behavior of the system at each step. • Examples: Puget Sound
Closed Loop • This scheme is designed to work several times, and each action relies heavily on the measured result/feedback of the previously taken action.	Open Loop • The open loop scheme uses actions off-line based on simulations of postulated scenarios and does not re-adjust its action to follow up on system progress.
Algorithmic Decision Based • This scheme has the capability to simulate system evolution faster than real-time, when long-term voltage instability is considered and the fast quasi steady-state simulation technique is used (Bacterial Foraging Algorithm, Particle Swarm Optimization)	Rule Based • This approach is found in a phase transformer scheme that sets initiating conditions, blocking transformer criteria, load shedding schedules, and possible events. (Fuzzy Logic, Expert System Rules)
Response Based • This scheme relies on the measurement of the voltage threshold through which the consequences of system mis-operation can be observed to adjust the corrective action based on disturbance severity. • Examples: Entergy, Southern Sweden	Event Based • This scheme operates based on the recognition of a particular combination of events. • Examples: Calgary

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***Authors**: Renuga Verayiah, Dept. of Electrical, Electronics and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi, Malaysia, Email: renuga@uniten.edu.my*
Prof. Dr. Azah Mohamed, Dept. of Electrical, Electronics and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi, Malaysia, Email: azah@eng.ukm.my
Dr. Hussain Shareef. Dept. of Electrical, Electronics and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi, Malaysia, Email: shareef@eng.ukm.my
Assoc. Prof. Dr.Izham Zainal Abidin, Dept. of Electrical Power Engineering, Universiti Tenaga Nasional, Malaysia, Email:izham@uniten.edu.my