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Research Note

Voltage Security Monitoring of Power Systems by a New Continuation Method

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Voltage security is an important concern in power networks as a result of system heavy loading. In this paper, a new continuation method is presented, which has three outstanding features for voltage security assessment. In this continuation method, adaptive step size is applied. For adaptation, a criterion, based on rate of voltage drop, is used. This method can monitor the voltage security status of power systems under various topologies, load levels and generation patterns. Different load and generation scenarios can be analyzed by this method. Also, the proposed continuation method uses local analysis for evaluation of power system voltage stability after contingency or preventive action. The proposed method has been examined on the test system of the New Zealand and Iran's power network. Obtained results confirm the validity of the developed approach. Also, the most vulnerable buses of these test systems have been sorted by a new ranking function. A discussion about this ranking function and its results has been presented.

INTRODUCTION

Voltage stability is an important subset of power system stability [1]. A power system is small disturbance voltage stable if its voltage levels are near predisturbance values after a small disturbance. In contrast, a power system undergoes voltage collapse if the post-disturbance voltage at equilibrium falls below acceptable range. Most voltage stability problems occur in response to large disturbances under heavy load conditions [2]. As current trends, due to deregulation and competition, increase, there is increased concern about voltage stability [1].

The System Dynamic Performance Subcommittee of the IEEE Power System Engineering Committee has defined voltage stability as the ability of a system to maintain voltage so that when load admittance is increased, load power will increase and both power and voltage are controllable [3]. Voltage instability is a type of system instability that occurs when the power system is unable to maintain an acceptable voltage profile under an increasing load demand and/or configuration changes. The System Dynamic Performance Subcommittee defined voltage collapse as the process by which voltage instability leads to very low voltage [3]. Voltage collapse of a power system may be caused by a variety of single or multiple contingencies such as a sudden removal of real and reactive power generation, a loss of transmission line or transformer or an increase in the system load without an adequate increase in reactive power.

The term voltage security means the ability of a system, not only to operate stably but, also, to remain stable following credible contingencies or adverse system changes [4]. Voltage security often means the existence of a considerable margin from an operating to voltage instability point following credible contingencies. From these definitions, it is found that voltage security and voltage stability are strongly related. More specifically, the same reactive power controllers can be used to improve both voltage security and stability [5]. If the system is unstable, the system must be insecure. However, if the system is insecure (e.g. voltage violation), the system may still be stable [5].

The phenomenon of voltage collapse has been observed in many countries and has been analyzed extensively in recent years. Several major network collapses caused by voltage instability problems were reported in France, Belgium, Sweden, Germany, Japan, the United States and Iran [2,6,7]. Most of the incidents are believed to be related to heavily stressed systems where large amounts of real and reactive power

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are transported over long transmission lines while appropriate reactive power sources are not available to maintain normal voltage profiles at receiving end buses. In some cases, however, voltage profiles show no abnormality prior to undergoing voltage collapse because of load variations. Operators may observe no advance warning signals until sudden significant changes in voltage magnitude result in the action of automatic protective equipment to crash the network [8]. Therefore, a tool which could provide timely evaluation of the voltage stability of a system under diverse operating conditions would be very useful.

Recently, a large number of papers have addressed the issue of quantifying the distance of a specific operating state to voltage collapse. In [9-11], the degeneracy of the load flow Jacobian matrix, its minimum singular value, its condition number and its vanishing eigen value/singular value were used as indices of power system small-disturbance voltage stability. The concept of multiple load flow solutions was proposed to deal with voltage stability problems in [12,13] and different voltage instability indicators were used to quantify the proximity of a particular operating state to the point of voltage collapse. These indicators can classify different power system conditions, but they also have disadvantages. Most of these indicators are discontinuous for the changing conditions of a power system and, also, require too long a computation time for practical power systems [14].

A more practical indicator is the distance between actual and maximum load at the stability boundary in the direction of an estimated or forecasted load increase [8,14-16]. The calculation can be done using the continuation method [15-17]. This method considers all nonlinearities of the power system, but is very time consuming for sufficient accuracy [14,18]. The energy method has also been used for voltage security assessment [8,18], but it is nonlinear and complex for numerical routines to solve. In [8,18,19], attempts have been made to set up a direct mapping from operating states to the Voltage Stability Margin (VSM), using the supervised Neural Networks (NNs). In [14], different power system conditions have been classified by using unsupervised NNs. NN based approaches for voltage stability determination are system dependent. A contingency or a preventive action can highly decrease the accuracy of these methods. Expert and fuzzy expert systems have been proposed for voltage security control [1,5], but these methods are dependent on the experience of operators and power system configuration.

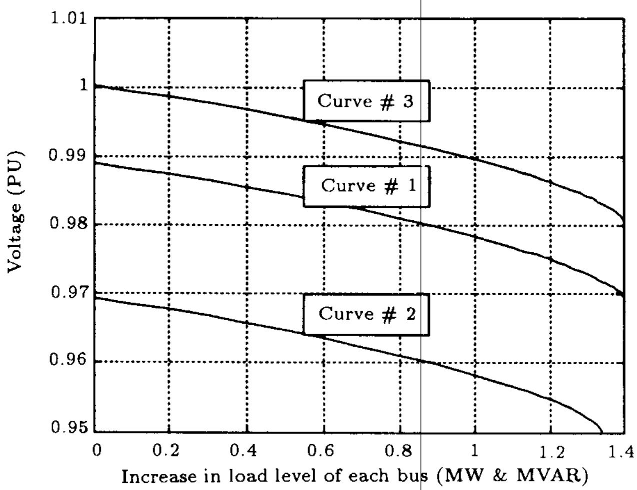
In addition, a considerable amount of work has been done on the understanding of voltage instability phenomena and the mechanisms that provoke voltage collapse [12,20-25]. There is no consensus on whether the voltage collapse mechanism is a steady-state [12,21,22] or dynamic [23-25] phenomena and, therefore, whether it should be analyzed by the relevant methods. This is perhaps due to the fact that voltage instability is a dynamic phenomenon that possibly lends itself properly to static analytical approaches [20]. Moreover, determination of the starting point of voltage instability is important in the remedying of this problem. Both operators and system planners require knowledge of the starting point of voltage instability.

Sensitivity analysis and modal analysis are well-known approaches to determine vulnerable areas of a power system [26]. For instance, sensitivity analysis has been used for determination of the starting point of voltage instability [8,18]. The proposed sensitivity analyses require too large an amount of data. Also, these methods suffer from lack of accuracy and, in some cases, obtained results do not match the expectations of experienced operators. Here, a kind of sensitivity analysis is proposed which can modify these imperfections.

THE PROPOSED METHOD

A continuation method is a well-known and efficient approach for analysis of static behavior and VSM determination of power systems. This method begins from a current operating point, which indicates the initial load level of the power system, then increases the load level step by step. In each step, the load flow of the power system is computed. This procedure continues until voltage collapse in the power system occurs. By increasing the load level of the power system, the number of iterations required for convergence of the load flow increases. In the continuation method, voltage collapse occurs at the load level where the number of required iterations for convergence of load flow goes to infinity. In other words, voltage collapse is at the point where load flow diverges. More details about the continuation method can be found in [15-17].

In Figure 1, execution of the continuation method for Iran's power network is shown (curve #1). As seen from this figure, by increasing the load level, bus voltages decrease until voltage collapse occurs. This curve is known as continuation curve or nose curve [15,27], in which voltage collapse is the last point or nose of it. VSM is the distance between a current operating point and voltage collapse on the nose curve. It is noted that this distance is VSM in the load domain. Similarly, VSM can be defined in the energy domain by using energy functions [8,18]. In this paper, VSM in the load domain has been used, since it is more comprehensible and easier to compute. In Figure 1, curve #1 is for normal operating conditions or the base case of Iran's power network. Curve #2 indicates the nose curve after a contingency (for instance, outage of a transmission line or a transformer). Curve #3 is the nose curve after



1) Base case; 2) Post-contingency; 3) Preventive action

Figure 1. Execution of continuation method for Iran's power network.

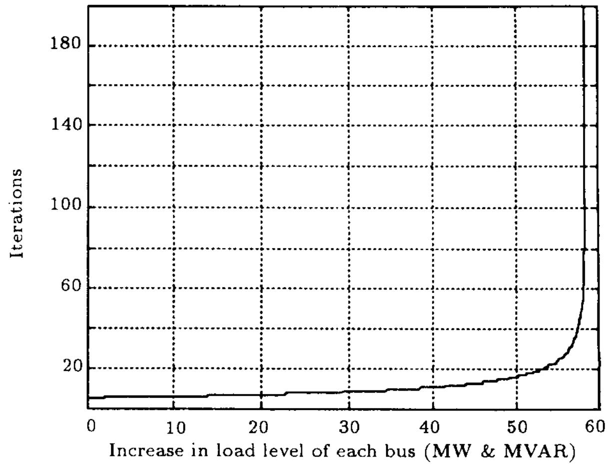


Figure 2. Number of iterations in the continuation method for the New Zealand test system.

a preventive action (for instance, adding an appropriate VAR source to the power system) [1].

Curves of Figure 1 have been obtained by monitoring the voltage of AHVAZ2, which is a 230 KV bus in the Khuzestan Power and Water Organization (KPWO). In Figure 1, increasing the load level was performed through increasing the active and reactive loads of all load buses having non-zero loads throughout the power system by the same step values, which are considered to be 0.1 MW and 0.1 MVAR. The 230 KV bus of AHVAZ2 is supplied by the Ramin and Modhedj power stations. This bus receives active and reactive power from these two power stations. The 230 KV bus of AHVAZ2 is connected to the Modhedj power station by two parallel transmission lines, which are MW 806 and MW 807. To obtain curve #2, the MW 807 transmission line has been outaged. To obtain curve #3, the 100 MVA capacitor bank (4× 25 MVA) has been added to the 230 KV bus of AHVAZ2. The generation level is increased, if possible, as the load level is increased. All generators contribute in increasing the generation level in respect of their governor rate and maximum generation capacity. In general, the proposed method solves this problem by using a scenario list, which is explained in the later section.

These curves of Figure 1 indicate the typical nose curves obtained by execution of the continuation method for Iran's power network. As observed from this figure, contingency usually decreases VSM, whereas preventive action can increase VSM. In Figure 2, the number of required iterations for the convergence of load flow versus an increase in load level for the New Zealand test system is shown. As seen from this figure, by increasing load level, the number of required iterations for convergence of the load flow increases and goes to infinity for voltage collapse.

Three new modules have been presented in the proposed continuation method. These modules are as follows:

a) Adaptation. Accuracy of the continuation method is dependent on the increments of load change. Smaller step size results in better accuracy of the continuation method, but increases the number of required load flows, which increases required computation effort. As seen from Figure 1, the rate of voltage drop in the vicinity of the collapse point is higher than the initial point. Thus, more load flow is required in the vicinity of the collapse point in comparison with the initial point. In other words, a smaller step size is required in the vicinity of the collapse point. Here, a variable step size is used, which results in the adaptive continuation method. The adaptive continuation method begins with an initial large step size and, as it proceeds, the smaller step size is considered. One problem, however, remains in this method. The collapse point is not known before the complete execution of the continuation method. Thus, a criterion for decreasing the initial step size is required. Here, the rate of voltage drop is used as this criterion. As the power system moves towards the collapse point, the rate of voltage drop (slope of tangential line to nose curve) increases and becomes infinity for the collapse point. The applied criterion for an adaptive continuation method is as follows:

$$S_c = \frac{(\partial|V|/\partial|S|)_c}{(\partial|V|/\partial|S|)_i}, \tag{1}$$

where S_c is the criterion value (slope value) for the current operating point. The numerator and denominator indicate the rate of voltage drop with respect to an increase in apparent power (MVA), for the current operating point and initial point, respectively. For calculation of this rate of voltage drop and by using the chain rule, it can be written that:

$$\partial|V|/\partial|S| = (\partial|V|/\partial P)(dP/d|S|) + (\partial|V|/\partial Q)dQ/d|S|). \qquad (2)$$

For this equation, it can be written that:

$$dP/d|S| = |S|/P, \quad dQ/d|S| = |S|/Q. \qquad (3)$$

Two remaining terms, i.e., partial derivative of voltage magnitude with respect to active and reactive power, can be calculated by using load flow equations and the Jacobian matrix [28].

There is no analytical method to determine the starting point of voltage instability in the power system. In the proposed criterion, S_c, rate of voltage drop is normalized with respect to the initial point, which gives a better insight for measuring the rate of voltage drop. The value of this criterion is different for different buses of the power system. Higher values of this criterion result in more vulnerable buses. Implementation of the continuation method in the state space can be considered as a trajectory from the current Stable Equilibrium Point (SEP) to the border of the region of attraction (ROA). ROA is a subspace of state space where the power system has feasible and stable operating points [29,30]. A smaller distance between the current SEP and the border of ROA results in a smaller VSM of the power system. Two factors can have an effect on this distance, the initial point of the trajectory or current SEP (current loading level of power system) and the border location of ROA (robustness of power system) [30,31]. The rate of voltage drop (numerator of criterion S_c) can describe the trajectory of the state space. In other words, higher rates of voltage drop indicate that the trajectory can reach the border of ROA faster or that the power system is weaker in terms of voltage stability. To consider the effect of the initial point of trajectory, the rate of voltage drop has been normalized with respect to the initial point of the continuation method. Thus, a higher value of criterion S_c can result in less distance between the border location of ROA and the initial point of the trajectory, which corresponds to a more vulnerable bus. A more vulnerable bus has more chance of being the starting point of voltage instability.

For the adaptive continuation method, the highest value of this criterion (the most vulnerable bus) is used. In each step of the adaptive continuation method, the highest value of S_c is determined, then the initial step size is divided into this value, which gives the step size for proceeding in the current operating point.

From a mathematical point of view, the proposed criterion implements a kind of sensitivity analysis. This criterion calculates the normalized sensitivity of the voltage magnitude, with respect to apparent power, for all buses of the power system. All buses of the power system are sorted according to this criterion. Higher values of this criterion for a bus result in a higher chance of that bus being the starting point of voltage instability. Thus, this criterion performs a ranking function.

b) Scenario List. For execution of the continuation method in a few previous works, such as PFLOW, the load level of all load buses has been increased by the same amount [15-17,20,27]. In all cases of practical power systems, the load level of all load buses does not increase uniformly. A practical power system may encounter different load scenarios. In the proposed continuation method, different load scenarios can be defined. The operator can specify the level of active power, reactive power or both, at which load buses must be increased for voltage stability evaluation.

Moreover, in a number of previous works, a few fixed generating buses, such as the swing bus, supply an increased consumption of active power in all cases [15-17,20,27]. In a practical power system, different generating buses can respond to a load scenario. In the proposed continuation method, the scenario list can contain different generation scenarios. The operator can specify which active power of which generating bus must be increased. The reactive power of generating buses is determined as the load flow output in each step of the continuation method.

c) Local Analysis for Contingency and Preventive Action. Contingency and preventive action can change the configuration of the power system. Thus, the VSM of a power system, after contingency or preventive action can be different in comparison with a base case (Figure 1). In many previous works, the VSM of the power system, after contingency or preventive action, must be computed separately [12-17,20,27]. In other words, the computation effort of the base case must be repeated for contingency or preventive action. Moreover, the configuration change of a power system is the main disadvantage of Artificial Intelligence (AI) based methods. For instance, after the configuration change of a power system, the training of NNs must be repeated by using new training samples or the knowledge base of expert systems must be revised [1,5,8,18,19].

The third module is dedicated to this purpose. The proposed continuation method can determine the nose curve of the power system after contingency or preventive action by using the nose curve of the base case, which greatly decreases the computation burden. For this purpose, the proposed continuation method uses local analysis, which begins from the pre-change operating point and results in an operating point after contingency or preventive action (Figure 3).

In Figure 3, Ei indicates an element, which escaped from the power system (contingency) or was inserted into power system (preventive action). For instance, this element can be a transmission line or a transformer. $B1$ and $B2$ are end buses of this element. Local analysis, by using the concept of electrical distance [32], defines three contours for the power system. The first two contours are about the end buses of this element (one contour for one end bus). Areas defined by these contours, i.e. $S1$ and $S2$, are considered as the most affected areas due to the configuration change. In these areas, the power system is exactly analyzed by using FDLF (Fast Decoupled Load Flow). The third contour is about two end buses. The third area, i.e., $S3$, is inside this contour and outside two other contours. This area is considered as the less affected area. In this area, the power system is approximately analyzed by using sensitivity factors. Sensitivity factors determine deviation from the initial operating point for the buses in this area [32,33]. Outside these three contours, $S4$ is slightly affected by the configuration change. Therefore, the effect of configuration change on this area is ignored and the previous operating point is considered instead. More details about local analysis can be found in [32,33].

Areas covered by these three contours, i.e. $S1, S2$ and $S3$, are proportional to the severity of the configuration change. The third module of the proposed continuation method, by means of local analysis, computes each point on the nose curve of the contingency or takes preventive action by using a corresponding point on the nose curve of the base case. The computation burden of local analysis for configuration change is much less than load flow analysis, while the accuracy of local analysis is acceptable. The computation burden of load flow analysis increases (Figure 2), especially about the collapse point but local analysis can rapidly determine this section of the curve by using the base case nose curve. The VSM of the power system, after contingency, is less than the base case (Figure 1). Thus, all points of the nose curve for contingency can be computed by using the base case nose curve. The VSM of the power system, after preventive action, is greater than the base case. Thus, a number of points of the preventive action nose curve can be computed by using the base case nose curve. The remaining points of the preventive action nose curve must be computed by means of load flow, since these points have no corresponding points on the base case nose curve.

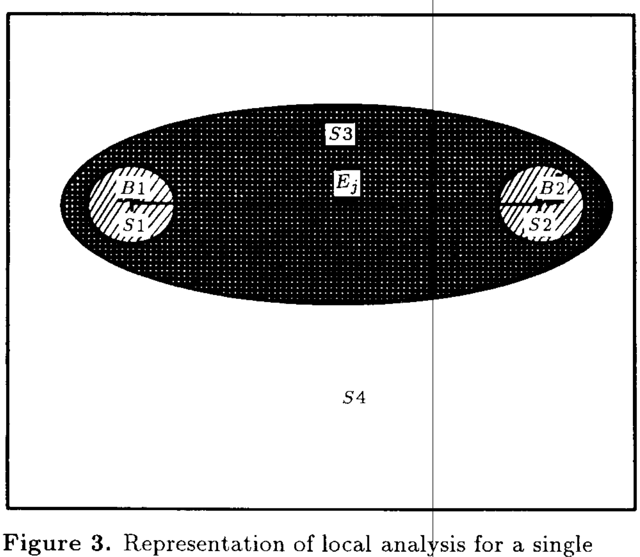


Figure 3. Representation of local analysis for a single contingency or single preventive action.

NUMERICAL RESULTS

The proposed continuation method has been examined on the test system of the New Zealand and Iran's power network. The test system of New Zealand is the reduced power system of the southern island of New Zealand. This test system has 17 buses, 20 transmission lines and 6 transformers, which can be considered as a small test system. This test system has a HVDC converter, which is modeled as a P-Q load and includes 11 KV, 14 KV, 16 KV and 230 KV voltage levels. The New Zealand test system is well-known and its data can be found in [19]. Another test system, used in this paper, is the Iran's power system network. This test system has 311 buses, 566 transmission lines and 124 transformers, which can be considered as a large test system and includes various voltage levels such as 11 KV, 13.8 KV, 20 KV, 63 KV, 132 KV, 230 KV and 400 KV. The data of Iran's power system network has been acquired from the national dispatching center of Iran [7].

The proposed continuation method requires two categories of input data which are as follows:

1. Input data for load flow analysis. This data is for the initial point of the continuation method and includes the reactive power limits of the generating units. The proposed continuation method determines the initial point of the nose curve by using this data. Then, this initial point is used for determining the next point of the nose curve. Generally, input data for each point of the nose curve is obtained from its previous point;
2. Input data for adaptation and scenario list. Format

of this input data is shown in Table 1, which is as follows:

2-1) P_{dt}: total increase in the active load of each bus,

2-2) Q_{dt}: total increase in reactive load of each bus. (In these two columns zero value indicates no increase.)

2-3) P_{ds}: initial step size for increasing active load of each bus.

2-4) Q_{ds}: initial step size for increasing reactive load of each bus. (The operator determines these initial step sizes according to the rate of increase of the active and reactive loads in different buses.)

2-5) P_{gt}: total increase in the active generation of each bus. P_{gt} is determined according to the available capacity of the generating units. Available capacity for each generating unit is calculated by deducting seasonal and operating limits from the installed capacity of that unit. For instance, in Iran's power network, the installed capacity of the gas turbine unit of the Ghom power station is 128 MW but, in summer, this unit can generate only 100 MW due to temperature rise (seasonal limit). As an another instance in Iran's power network, the installed capacity of the steam unit of the Ramin power station is 315 MW, but this unit can generate a maximum of 305 MW, due to the condenser vacuum drop (operating limit). This data can be obtained from ISO, the entropy and capability curves of the generating units [34], which are provided by the manufacturer. For instance, this data for the generating units of Iran's power network is available in the PAS (Power Application Software) database of the national dispatching department.

2-6) P_{gr}: loading rate of the generating units. The loading rate of a generating unit can be obtained from its ramp rate curve [34], which is supplied by the manufacturer. For instance, this data for the generating units of Iran's power network is available in the PAS database of the national dispatching department.

The first four parameters describe the load scenario that the operator wants to analyze. For the operational mode of the power system, these parameters can be obtained from STLF (Short-Term Load Forecasting) packages. For instance, in the national dispatching department of Iran's power network, this data can be obtained from the FOC software package, which is a utility of PAS [35].

Table 1. Input data for adaptation and scenario list.

Bus No.	P_{dt}	Q_{dt}	P_{ds}	Q_{ds}	P_{gt}	P_{gr}

Also, using the column of P_{gr}, the proposed continuation method determines the initial step size for increasing active generation of each bus. For this, the sum of the initial step sizes of the active load, or P_{ds} values, is calculated. This summation indicates an increase in the active load of the whole power system in the first step of the continuation method, which is, then, distributed among generating buses, according to their loading rates:

$$P_{gsi} = \frac{P_{gri}}{\sum_{j=1}^{n} P_{grj}} \times \sum_{j=1}^{n} P_{dsj},$$

$$i = 1, 2, \cdots, n. \tag{4}$$

In this equation, P_{gsi} is the initial step size for increasing active generation of the ith bus and n is the number of buses. If, for instance, the ith bus has no generating unit or its units cannot increase their active generation ($P_{gti} = 0$) then zero is entered for P_{gri} and P_{gsi} becomes zero. If, for the ith bus, the entered value for P_{gti} is greater than zero but, during the execution of the continuation method, active generation of this bus reaches its limit, then the continuation method inserts zero for P_{gri}, which causes active generation of this bus not to be increased any further. After this step, an increase in the active load of the whole power system is distributed among the remaining generating units. If, in a step, the active generation of all generating buses reaches their limit, then the power system cannot supply an increase of active consumption. In this case, the balance between active load and generation is not kept and the frequency of the power system begins to drop. If frequency drop is more severe than voltage drop, then the power system may be trapped in dynamic instead of voltage instability. In this case, the proposed continuation method continues the defined scenario to determine the voltage collapse point but, at the same time, describes the situation for the operator.

After initialization of step sizes, in each step of the continuation method, initial step sizes of load and generation:

$$P_{dsi}, Q_{dsi}, P_{gsi}, \quad i = 1, 2, \cdots, n. \tag{5}$$

are refined according to the current step. For doing this, the initial step sizes of load and generation are divided to the highest value of S_c for the current step. Since the step sizes of the active load and generation are refined by the same factor, the balance between load and generation is not damaged by this refinement.

Obtained results from the proposed continuation method, normal continuation method and neural network, for VSM determination of the New Zealand test system in 10 different situations with different topologies, are shown in Table 2. Test errors and computation times are average values for 10 cases. For NN, two computation times must be mentioned that are training time (the first mentioned time) and test time (the second mentioned time). The average number of training samples for all test cases is 160 [18]. This NN has a Multi-Layer Perceptron (MLP) structure and an Error Back-Propagation Learning (EBPL) algorithm, which are the same as those used in [8].

In all 10 test cases, the load level of all load buses is increased uniformly and the swing bus supplies an increased consumption of active power. For instance, the obtained results for the first test case have been shown in Table 3. As seen from this table, maximum loading capacity for the New Zealand test system, in this test case, is 577 MVA. This number is VSM in the load domain for the whole test system. If the load level of the New Zealand test system, with the configuration of this test case, increases by 577 MVA, while this increase is uniformly distributed among all load buses (load scenario) and the swing bus supplies a total increase in active power (generation scenario), then voltage collapse occurs in this test system. The relative error of NN, normal continuation method and the proposed method for this test case are shown in Table 4. This relative error has been computed by the following equation:

$$RE = |\text{Actual result} - \text{Obtained result}|/\text{Actual result}, \quad (6)$$

where RE indicates the relative error. In this test case, the proposed continuation method reduces step sizes by 8.7 times. In other words, initial step sizes are 8.7 times the final step sizes.

To compare different approaches, the third module or local analysis of the proposed continuation method has not been applied for the results of Table 2.

Table 2. Comparison of the proposed continuation method, normal continuation method and NN.

Approach	Test Error (%)	Computation Time (s)	
The proposed method	1.07	19	
Normal continuation	1.09	86	
NN	1.33	858	0.2

Table 3. Obtained results for the maximum loading capacity (in terms of MVA) of the New Zealand test system.

Actual	NN	Normal Continuation Method	The Proposed Method
577	569	583.5	583 MW

Table 4. Relative error of NN, normal continuation method and the proposed method.

NN	Normal Continuation Method	The Proposed Method
1.39 %	1.13 %	1.03 %

In other words, the proposed continuation method determines the VSM of each situation separately, since in this table, only the adaptation module needs to be evaluated. As seen in Table 2, with approximately the same test error, the computation time of the proposed continuation method is much less than that of the normal continuation method. With the same test error, the number of required load flows in the adaptive continuation method is much less than that of the normal continuation method. The test error of the NN is slightly more than that of the proposed continuation method. The NN has a short response time (test time) but its training is a lengthy process. If the configuration of the power system is fixed, then the NN requires one training process. For this case, NN is a good approach but, if configuration of the power system changes, then, NN requires new training samples and the training process of the NN must be repeated. The computation time of NN training is about 10 executions of the normal continuation method and 45 executions of the adaptive continuation method. Thus, efficiency of the NN depends on the type of application. More details about comparison of NN and the continuation method for VSM determination can be found in [18].

Six real scenarios of Iran's power network, which encountered voltage collapse, have been analyzed by the proposed continuation method. Each test case has a separate load and generation scenario.

Obtained results from the proposed continuation method for these test cases are shown in Table 5. In this table, the column of "Actual Result" indicates the VSM of the whole Iran's power network, due to the applied configuration, load and generation scenario. For instance, in scenario no. 1, a load of 113 buses is changed in the load scenario and 23 buses contribute to the generation scenario. In this scenario, input data

Table 5. Obtained results for the maximum loading capacity (in terms of MVA) of Iran's power network for different scenarios.

Scenario No.	Actual Result	Obtained Result	Error (%)	Computation Time (s)
1	461.8	455.7	1.32	805
2	671	664.2	1.01	908
3	1311.1	1327.2	1.23	1108
4	1696.1	1666.6	1.74	1305
5	1844.6	1824.6	1.08	1224
6	2144.1	2125.5	0.87	1478

for bus # 90 or "TABAS-7" are as follows:

$$P_{ds90} = 0.4 \text{ MW}, \ Q_{ds90} = 0.4 \text{ MVAR}, \ P_{gr90} = 0 \text{ MW},$$
$$P_{dt90} = 6 \text{ MW}, \ Q_{dt90} = 5.7 \text{ MVAR}, P_{gt90} = 0 \text{ MW}. \quad (7)$$

"TABAS-7" is a 132 KV bus in Iran's power network. In this scenario, the active and reactive loads of this bus are increased, but active generation of this bus has no increase, since this bus has no generating unit. In scenario no. 1, input data for bus #19 or "BST12-4" are as follows:

$$P_{ds19} = 0 \text{ MW}, \ Q_{ds19} = 0 \text{ MVAR}, \ P_{gr19} = 2 \text{ MW},$$
$$P_{dt19} = 0 \text{ MW}, \ Q_{dt19} = 0 \text{ MVAR}, \ P_{gt19} = 40 \text{ MW}, \quad (8)$$

"BST12_4" is a 13.8 KV bus in Iran's power network. In this scenario, the active and reactive loads of this bus have no increase. This bus has two generating units (steam units), which contribute to the generation scenario. In this scenario, input data for bus # 148 or "TBRZS_4" are as follows:

$$\begin{aligned} &P_{ds148} = 0.8 \text{ MW}, && Q_{ds148} = 0.4 \text{ MVAR}, \\ &P_{dt148} = 12 \text{ MW}, && Q_{dt148} = 3 \text{ MVAR}, \\ &P_{gr148} = 6 \text{ MW}, && P_{gt148} = 116 \text{ MW}. \end{aligned} \quad (9)$$

"TBRZS-4" is a 20 KV bus and has four generating units (two steam units and two gas turbines). In this scenario, the active and reactive loads and active generation of this bus are increased. This bus contributes to both the load and generation scenarios.

Input data for other buses are inserted similar to the above examples. In this test case, the proposed continuation method reduces step sizes by 8.5 times. For analysis, these six real scenarios, including first and second modules, i.e., adaptation and scenario list, have been used. Average test error and computation time for these six scenarios are 1.21% and 1138 s (18' and 58"), respectively. For Iran's power network, error and, especially, computation time are larger than for the New Zealand test system. This is due to the size and complexity of Iran's power network in comparison with the New Zealand test system. Moreover, scenarios of Iran's power network (including load and generation scenarios) are more complex than the applied scenario for the New Zealand test system. In spite of these conditions, the accuracy of the proposed continuation method for Iran's power network is acceptable.

In cases 3 and 5 of these six scenarios, active generation of all generating buses reaches its limit and unbalances between the time active load and active generation occur. The proposed method detects saturation of the generating units in these two cases and prompts the operator about the probability of dynamic instability. Then, the method proceeds until the voltage collapse point is obtained. It is noted that the proposed continuation method can only detect the probability of dynamic instability, but cannot analyze it. This is due to the fact that dynamic instability is essentially a dynamic phenomenon and cannot be analyzed by static analytical methods.

For examination of the third module or local analysis, the configuration of Iran's power network in case 2 of Table 5 is considered as the base case. Then, two real contingencies and one real preventive action are considered for this configuration, which are as follows:

1. Contingency #1. In this contingency, forced outage of the transmission line between buses SLMI-9 and JALAL-9 occurs. This is a 400 KV transmission line and its length is 253 km. In the base case, this transmission line carries 576.25 MW and 146.83 MVAR from the sending bus, which indicates that this line is stressed. Loss of this transmission line is 13.89 MW and -5.58 MVAR (reactive power of receiving bus is more than sending bus);
2. Contingency #2. In this contingency, outage of the transformer between buses ALABD-9 and ALABD-8 occurs. This is a 400 KV/230 KV and 500 MVA transformer with a fixed tap. In the base case, this transformer works at its nominal point;
3. Preventive Action. In this preventive action, a shunt capacitor is added to bus ESFRA-9. The available capacity of this shunt capacitor is 98.1 MVAR.

Results obtained from the normal and proposed continuation method, without/with local analysis for these three test cases, are shown in Table 6. In this table, the column "Actual Result" indicates the VSM of the whole Iran's power network in Iran (in terms of MVA) after contingency or preventive action. The normal continuation method and the proposed continuation method without local analysis solve these three test cases separately. The proposed continuation method with local analysis determines the VSM for these three test cases by using the nose curve of the base case. Here, adaptation is used for the proposed continuation method. As seen from this table, contingency #1 and #2 decrease the VSM of the power system in comparison with the VSM of the base case (671 MVA). In contrast, preventive action increases the VSM. The computation time for local analysis of preventive action is slightly more than contingencies. This is due to the fact that all points of the contingency nose curve can be computed by using the nose curve of the base case, but the points of the preventive action nose curve, which have no corresponding points on the base case nose curve, must be computed by using load flow. Average values of the "Error" columns in Table 6 are 1.17%, 1.14% and 1.52%, respectively. Average

Table 6. Numerical results of the normal continuation method, the proposed continuation method without local analysis and the proposed continuation method with local analysis for Iran's power network.

Test Case No.	Actual Result	Obtained Result(1)	Error (%)(1)	Computation Time (s)(1)	Obtained Result(2)	Error (%)(2)	Computation Time (s)(2)	Obtained Result(3)	Error (%)(3)	Computation Time (s)(3)
1	628.8	620.2	1.37	3716	621.1	1.22	904	618.8	1.59	67
2	648.9	642.5	0.99	3848	641.5	1.14	916	637.5	1.76	66
3	693.2	701.2	1.15	3988	700.5	1.06	968	701.6	1.21	88

(1): The normal continuation method,

(2): The proposed continuation method without local analysis,

(3): The proposed continuation method with local analysis.

Table 7. Decrease in computation times.

Test Case No.	Computation Time (s)(1) / Computation Time (s)(2)	Computation Time (s)(1) / Computation Time (s)(3)	Computation Time (s)(2) / Computation Time (s)(3)
1	4.11	55.46	13.49
2	4.20	58.30	13.88
3	4.12	45.32	11.00
Average	4.14	53.03	12.79

values of the "Computation Time" columns in this table are 3851 s, 929 s and 74 s, respectively. This shows that although error in local analysis is slightly more than that of the two other methods, computation time of the local analysis is much less. This capability enables the proposed method to rapidly analyze a configuration change in the power system. It is noted that local analysis can only analyze single contingencies and single preventive actions. In practice, it was observed that in multiple contingencies or multiple preventive actions, interaction between different configuration changes usually increased the error in local analysis.

Decrease in computation time for the proposed continuation method without/with local analysis, in comparison with the normal continuation method, has been shown in Table 7. As seen from this table, the proposed continuation method with local analysis can effectively decrease computation time.

Buses of the New Zealand test system and Iran's power network have been sorted according to the explained criterion (S_c) and results are shown in Table 8. In this table, the 10 most vulnerable buses of these test systems have been represented and ranked in order of severity.

For calculation of criterion S_c, the case presented in Table 3 for the New Zealand test system and case 6 of Table 5 for Iran's power network have been considered. In both cases, criterion S_c has been computed for the last point of the proposed continuation method. In other words, the last point in the nose curve has been considered as the current operating point (numerator of S_c).

Table 8. Obtained results from criterion S_c.

No.	New Zealand Test System	Iran's Power Network
1	ROXBURGH-220	TABAS-7
2	LIVINGSTN220	FRDOS-7
3	INVERCARG220	BSHRO-7
4	TIWAI-220	BIRJN-7
5	BENMORE-220	SAHLA-7
6	BROMLEY-220	GHAEN-7
7	ISLINGTON220	GONAB-7
8	ROXBURGH-011	FEYZA-7
9	MANAPOURI220	TORBH-7
10	MANAPOURI014	BARD-7

As observed from Table 8, from the voltage stability point of view, ROXBURGH-220 is the most vulnerable bus of the New Zealand test system and TABAS-7 is the most vulnerable bus of Iran's power network. The nose curve for the most vulnerable bus of the New Zealand test system and Iran's power network are shown in Figures 4 and 5, respectively. Results of Table 8 coincide with knowledge of the power system by expert operators. For example, ROXBURGH-220 in the New Zealand test system encounters a lack of reactive power, which results in the low VSM of this bus. In another instance, consider TABAS-7

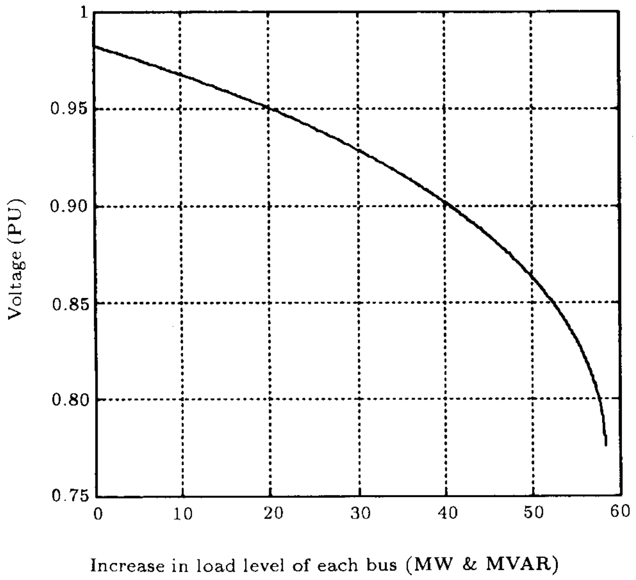


Figure 4. Nose curve for the most vulnerable bus of the New Zealand test system.

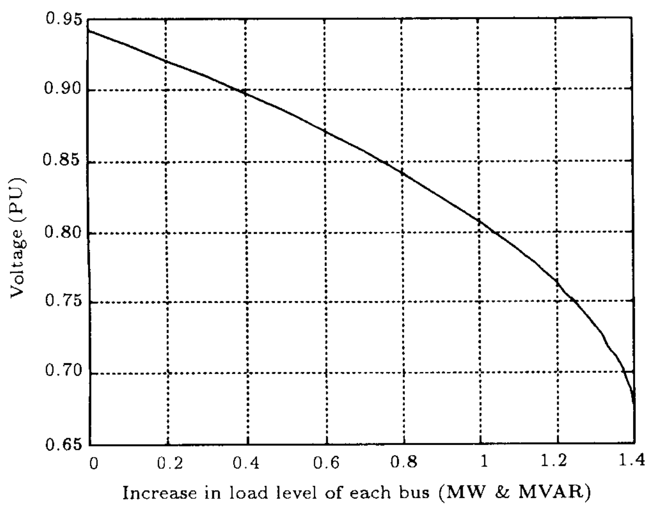


Figure 5. Nose curve for the most vulnerable bus of Iran's power network.

and FRDOS-7, which have been determined as being the most vulnerable buses in Iran's power network. TABAS-7 and FRDOS-7 are the end buses of 132 KV radial links in the Khorasan REC (Regional Electric Company) of Iran's power network. Thus, these buses usually encounter the problem of low voltage (less than 132 KV), however, these buses have been designed to work at 132 KV. In other words, these buses usually operate at less than the designed value, which increases the vulnerability of these buses to voltage contingencies. This causes a weakness in TABAS-7 and FRDOS-7 in terms of voltage stability. This problem can also be explained from a mathematical point of view. Voltage collapse of each bus occurs at a specific voltage, which depends on the robustness of the bus and the network configuration. For instance, voltage collapse for TABAS in Iran's power network occurs at about 90 KV. If the operational voltage of this bus, which corresponds to the initial point of its nose curve, decreases, the distance between operational and collapse voltage decreases. In other words, the VSM of this bus in the voltage domain decreases. If the decrease in the operational voltage continues, the VSM of the voltage domain decreases until the collapse phenomenon occurs at the initial point of the nose curve. In this case, the nose curve of this bus disappears and no operating point for the power system can be defined.

As can be seen from the nose curve, there is a one to one and monotonic mapping relation between the VSM in the voltage and load domain [27]. Thus, decrease in the VSM of the voltage domain results in a decrease of VSM in the load domain. Therefore, if the operational voltage of TABAS-7 becomes less than the designed value, the VSM of this bus in the load domain decreases. This causes TABAS-7 to appear as a weak bus, in terms of voltage stability. The experience of operators at the national dispatching department (Iran's power network) confirm this assertion.

In addition to the VSM of the whole power system, the VSM of buses must also be considered. Generally, different buses in a power system have different VSMs. More vulnerable buses have smaller VSMs. The most vulnerable bus which has the smallest VSM determines the VSM of the whole power system. The VSM in the load domain (increase in load level) for the most vulnerable bus of the two test systems are shown in Figures 4 and 5.

The criterion S_e uses only the load flow data. Large computation and data are not required in this criterion.

All programs in this paper have been written in visual C++ and all execution times have been measured on a Pentium P233 personal computer. The CPU speed of this computer is 225 MHZ.

CONCLUSION

Voltage security problems are one of the major concerns for electric utilities, as a result of system heavy loading. In this paper, a new continuation method is used for the voltage security monitoring of electric power systems which has an adaptive step size. For adaptation, a criterion based on the normalized rate of voltage drop, is applied, which performs a ranking function. The proposed continuation method can monitor the voltage security status of power systems under various topologies, load levels and generation patterns. Different load and generation scenarios can be analyzed by this method. Also, the proposed continuation method uses local analysis for evaluation of power system voltage stability after contingency or preventive action. The proposed continuation method and ranking function have been examined on the test system of the New Zealand and Iran's power system network. Also, a discussion about obtained results has been presented.

Research work is underway in order to: 1) Develop a comprehensive model for dynamic loads of power systems; 2) Quantify the distance between the current operating point and dynamic instability point; 3) Extend the local analysis to include the multiple contingencies and multiple preventive actions with acceptable error; 4) Develop a ranking function for voltage contingencies by means of an electrical distance concept.

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