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Restoring desired voltage security margin based on demand response using load-to-source impedance ratio index and PSO

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ABSTRACT

Demand Response (DR) is an active role of end-users in responding to signals coming from the market or to emergency signals coming from system operators, asking for a load reduction to help facing criticalities and reduce blackout risks. Load reduction is one of the typical DR participation methods for large and small consumers which is generally considered as a final defence strategy against system instability when voltage collapse is anticipated and may potentially result in blackout. In this paper, an algorithm concerning load reduction based DR is proposed. Indeed, a two-state algorithm based on finding optimal load reduction pattern and estimating threshold voltage of initiating DR is presented to prevent power system from voltage collapse. In this regard, load-to-source impedance ratio (Z_L/X_{Th}) is adopted as an index for evaluating voltage security margin (VSM) and is utilized in an optimization algorithm aimed at obtaining minimum load to be cut down. The proposed approach has been implemented in IEEE 39-bus network demonstrating its effectiveness and applicability.

1. Introduction

Demand Response (DR) refers to the changes of the electric load profile by end-use customers with respect to their normal consumption patterns, in response to electricity price variations over time or to signals coming from the system when its security or reliability is jeopardized, according to programs designed to obtain a lower electricity use. These programs concur to relieve the system from undesired or unexpected critical conditions [1]. One of the probable threats in any electric power system is blackout resulting from voltage collapse which has become more frequent in industrial countries because of some operational factors like network deficiencies and continuous load growth. In order to rescue an unstable system from total blackout, load reduction is considered as the ultimate countermeasure when there are no other alternatives to stop an approaching collapse. In power system's operational planning studies, system operators evaluate system security under various working conditions ahead and take appropriate remedial actions in advance to fulfill all security criteria. These remedial actions consist of voltage control resource adjustments (transformer taps, shunt reactors and generation bus voltages), modification of generation dispatch (increase/decrease of generation in several units and starting up new units) and load pattern [2,3].

Several works have been proposed on DR incorporated in power system operation and stability. In [4], the focus of paper is on Interruptible/Curtailable service and capacity market programs, which are incentive-based DR programs including penalties for customers in case of no responding to load reduction. In [5], a scenario-based modelling approach for corrective voltage control of power systems in presence of the uncertainty of wind power generation and demand values is presented. In [6], an event-driven emergency DR scheme is proposed to prevent a power system from experiencing voltage collapse. In [7], a strategy for optimal DR control based on the management of highly-distributed electric loads is presented to meet transmission-level control aimed at maintaining voltage stability. In [8], the utilization patterns of the DR resources from a system operation point of view, their impact on the operation of competitive markets, unit commitment solutions, and on market prices are analyzed.

In [9], a LP-based optimizing load shedding algorithm is presented to improve the load margin. The objective function consists of minimizing the total system demand decrease. A load shedding scheme against long-term voltage instability is proposed in [10]. A distributed scheme has been presented in which load shedding tends to act first where the voltages drop the most. In [11], an optimal load shedding problem is formulated to minimize the sum squares of the difference between the connected loads and the generated powers. In [12], based on the increasing of the number of participants, an approach for load

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Nomenclature

DR	demand response
LR	load reduction
PSO	particle swarm optimization
VSM	voltage security margin
VSM*	desired voltage security margin
O.F.	objective function
$X_{Th,k}$	equivalent network reactance at bus #k
$Z_{L,k}$	load impedance at bus #k
(Z_L/X_{Th})	load-to-Source Impedance Ratio
$(Z_L/X_{Th})^*$	desired value of Z_L/X_{Th} index corresponding to VSM*
$(Z_L/X_{Th})^{crit}$	load-to-Source Impedance Ratio for the most critical event
$\Delta(Z_L/X_{Th})^{Permissible}$	permissible amount of decreasing load-to-source impedance to loadability limit
$(Z_L)^{min}_{secure}$	minimum secure load impedance corresponding to VSM*
$(Z_L/X_{Th})^{min}_{secure}$	minimum secure load-to-source impedance ratio corresponding to VSM*
$V_{DR}^{Threshold}$	threshold voltage of demand response
α	percentage of base load
Pmax	network loadability limit
P_{red}	amount of load reduction

shedding program is presented. This load control strategy is able to split every user's load into interruptible and uninterruptible parts, and subsequently to perform load shedding on the interruptible parts only. The optimal load reduction request is found by minimizing the expected value of an appropriate cost function, thus taking the uncertainty about the power absorbed by each customer into account.

In [13], an optimization model is proposed to minimize the load curtailments necessary to restore the equilibrium of operating point with relaxation of restrictions. Analytical description of the design of several load-shedding schemes for the protection of the Hellenic Interconnected System against the risk of voltage collapse is presented in [14]. In [15], the concept of residential consumers "soft" load shedding (SLS) is proposed. It takes only a fraction of the consumers' power, even if the effort is spread over a larger number. In [16], a criterion which is directly based on the definition of voltage stability is proposed for the purpose of load shedding. It calculates the derivative of apparent power against load admittance (dS/dY). This approach presents a method of estimating VSM which utilizes local measurements and applied criterion which is based on the very definition of the voltage stability. In [17], an integer-value modelling for optimal under voltage load shedding is presented. Load feeders of load buses by assigning interruption penalty factors are applied to modelling resulting to minimize total number of participating buses in load shedding and total interruption cost. In [18], an anticipatory load shedding methodology determining optimum load to be shed at selected buses based on voltage stability is proposed. The buses for load shedding have been selected based on the sensitivity of minimum eigenvalue of load flow Jacobian matrix. In [19], a transfer impedance based system equivalent model for voltage stability analysis is presented. Identifying the weakest buses and system voltage stability and also calculating the amount of real and reactive power transferred from generators to vulnerable node causing voltage instability is developed. In [20], a two sub-problems based algorithm named by restoring solvability sub-problem and improving VSM sub-problem is presented. Solving each sub-problem is carried out using linear optimization based optimal power flow. In [21], a preventive countermeasure is proposed to improve voltage stability margin through the management of the reactive power and its reserve. This scheme is developed to distinguish and to improve the effective reactive power reserve of the generators.

The majority of relevant researches conducted on voltage stability have proposed some preventive or corrective methods. Several research works have studied on the Thevenin equivalent estimation or its application in voltage stability assessment. The remainder have analyzed the effect of demand side management on system operation or market operation. While the issue of the application of load-to-source impedance ratio in the estimation of an optimal load reduction pattern in DR programs which has not been addressed in any work yet, becomes the main concern of this paper.

In order to preserve voltage security margin through DR, two parameters should be determined properly; 1- the threshold voltage for initiating DR, 2- the minimum amount of load reduction. The critical threshold voltage is considered as a criterion for performing load reduction. In fact, the threshold voltage is an indicator representing the boundary between secure and insecure voltage regions which is equivalent to desired voltage security margin. The amount of load reduction can be generally estimated by some indices and optimization methods based on preserving minimum required VSM.

In this study, we assume that all power system loads participate in security market voluntarily and are become involved in DR program. In other words, since the maximum permissible load reduction for each load bus would be different considering its preparation for participation in DR programs, it is assumed that all participants are prepared to take part in DR up to a certain percentage of their load level ensuring the security of power system against voltage collapse and then the customers are offered payments based on the amount of their load reduction. In this regard, a two-state algorithm is proposed to deal with both parameters of load reduction for preserving minimum required VSM which is named desired voltage security margin (VSM*). Concerning VSM*, the proposed approach determines the value of critical threshold voltage or minimum required load reduction. In the first state, the threshold voltage is called as a criterion indicating the time and location of load reduction but not exactly minimum amount of one. The most interesting feature of this state of the approach is its quickness and accuracy in calculating the critical threshold voltage at one step prior to the time of implementing DR. In the second state, the minimum amount of load reduction aimed at improving voltage stability is estimated by recognizing the most effective buses using (Z_L/X_{Th}) index and PSO. Hence, an accurate estimate of load reduction pattern comprising its location and minimum amount along with ensuring desired voltage security is taken into account as the most dominant feature of this state.

2. Demand response

DR comprises a wide variety of contractual and service agreements based on the voluntary participation of the users to specific programs. DR programs may be categorized as incentive-based or price-based programs. In incentive-based programs the customers are offered payments in order to deliver a specific amount of load reduction over a given time period, while in price-based DR programs consumers voluntarily provide load reductions by responding to economic signals [22]. The seller of the DR programs is the electricity user and the ultimate buyer is the grid operator or the trader. The user is able to produce their response by shutting down some of the electrical appliances they are using, by turning on a local generator or at a more sophisticate level by controlling their total power consumption and/or production. The energy manager will take appropriate decisions considering the compulsory or voluntary nature of the received request, and will optimize the economical aspects of the action with respect to the specific program to which they are responding. Emergency programs are also designed to provide sufficient security margin, i.e. the reduction of electricity consumption offered by consumers will be used to face power grid emergencies such as faults of system components and