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Centralized coordination of emergency control and protection system using online outage sensitivity index

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ABSTRACT

This paper determines the best locations for centralized load shedding considering the protection systems that can be monitored from transmission system to avoid cascading failures. The vulnerability of power system integrity is determined and ranked using online outage sensitivity index (OSI) considering ampacity of transmission lines, over excitation of generators and transformers, under frequency and under voltage protection relays and low voltage ride through capability of grid connected renewable energy sources. The power system elements are ranked based on the results of outage sensitivity index (OSI) to concentrate the load shedding as control action on areas containing most critical elements prone to outage. The efficiency of proposed multi objective approach is validated through numerical simulations of severe contingencies carried out in DigSilent Power Factory software on 39 bus IEEE standard test system.

1. Introduction

Power system is the largest physical human-made infrastructure with thousands of sophisticated electrical equipments. Despite of observability of its state variables in the control center, even expert operators may not be able to make complicated decisions in the short time period of emergency control following severe disturbances. Implementation of independent and more importantly uncoordinated protection systems makes the situation even worse. Therefore, the power system operation and control should be equipped with automatic self-healing control schemes to protect the power system integrity and then stability of entire network against cascading failures.

Planning for contingencies is essential for secure and reliable operation of network. Generally, system security comprises of three recursive tasks that are consistently carried out in the control center. *system monitoring (SM)* is the first task in which the performance of power system equipment in transmission level can be monitored from control center to detect the violation from operation limits. In the second task, i.e. *outage sensitivity index (OSI)*, vulnerability of power system integrity due to out of range operation of equipment is ranked in term of their violation severity. The severity of outage can be ranked based on multiple criteria, i.e. the available time prior to the outage, the losable apparent power of tripped element and the voltage drop. Finally, in the third task, i.e. *corrective measure (CM)*, the grid operator in the control center can make decision/s based on the location of critical elements ranked based on the outage sensitivity index (OSI). The elements with higher OSI are prioritized as the target of existing control action.

The majority of recent and relevant literatures focus on centralized load shedding to estimate load-generation mismatch using frequency gradient [1–6]. The proposed methods are strongly dependent on system inertia and network topology, which may be easily challenged in the presence of low or no inertia generation sources such as inverter-based renewable energy sources [7]. Besides, in these methods, the estimation of active power deficit is based on frequency gradient, which is not reliable always and needs to be supervised by another variable as is recommended by relevant standards [8].

Distributed strategy of load shedding suggested in [9–12] is based on locally measured voltage and frequency data and therefore is independent of power system parameters. These methods can deal with integration of renewable energy sources into power system, cascading events and islanding condition. Although, the aforementioned decentralized methods are reliable against recent cyber security issues resulting from required communication link, having no supervision and management from control center is their major drawback.

While considering the voltage dynamics is strongly recommended by relevant standards [8], only Refs. [9,1,4,5,3,12] involve the voltage data in their method, which possesses an exclusive category in stability

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Nomenclature

OSI	outage sensitivity index
SM	system monitoring
CM	corrective measure
LVRT	low voltage ride through
OC	over current
UV	under voltage
UF	under frequency
OE	over excitation

study [13]. Voltage variation can directly affect both active and reactive power of loads, the power imbalance and therefore, the Rate of Change of Frequency (ROCOF). Besides, involving the voltage drop with the scheme, makes the method adaptive to the event location.

This paper focuses on load shedding as control action, which is the last and most expensive barrier against blackouts. Current work, not only overcomes the deficiencies elaborated in the above paragraphs, but also it includes the advantages of above reviewed literatures in addition to the following solid contributions. First, despite of reviewed methodologies, the control action/s are coordinated with the protection system to prevent cascading failures by considering the power system elements prone to trip due to violation from their operating limits. Furthermore, outage sensitivity index (OSI) is performed online based on severity/scale of outage/s, the available time frame until outage and the voltage drop magnitude. Besides, the grid codes, e.g. Fault Ride Through (FRT) capability regulated for solar and wind farms has been included, which makes the solution feasible and applicable for future power systems with high share of renewable energy sources.

One of the major contributions of the current paper is to suggest a method independent of power system inertia, which is essential for existing methods of load shedding called *System Frequency Response (SFR)*. In this techniques, the active power deficit is estimated based on Rate of Change of Frequency (ROCOF). Despite of all these methods, our proposed method does not rely on ROCOF variable, which strongly depends on system inertia. Our method is suitable for networks with high share of renewable energy sources in which the inertia is unknown or at least uncertain.

Despite of discussed methods, the current work does not rely on uncertain inertia of the network. Instead, the proposed technique adaptively detects the best locations for execution of control action to relief the burden of overloaded equipment. As mentioned, any out of range of variables may trigger the load shedding in the critical locations chosen based on maximum OSI, which completely differs our method from existing methods. If during the load shedding, there is no overloaded element in the network, but the frequency still keeps on falling, the control action will be continued in the locations with lower voltage magnitude until proper recovery trend of frequency is detected. If the load shedding is done in the locations with higher voltage magnitude, there is the risk of triggering the over excitation protection relays. Since the frequency is still low and execution of load shedding further increases the voltage leading to high values of V/f criterion.

This paper is organized as follows: comprehensive power system monitoring (SM) regarding violation from permissible operation range of elements is presented in Section 2. An online and integrated outage sensitivity index (OSI) is developed in Section 3. Orientation of corrective measures (CM) according to the results of outage sensitivity index (OSI) is performed in Section 4. The simulation set up and results are presented in Section 5. Finally, the paper is concluded in Section 6.

2. System monitoring (SM)

Different and independent protection schemes are installed on the power system elements to protect them against long operation in abnormal and out of range conditions. Under frequency (UF) protection of Synchronous Generator, thermal overload or over current (OC) protection of transmission lines and transformers, over excitation (OE) of synchronous machines and transformers and low voltage ride through (LVRT) grid code for non-synchronous generators are among well-known protection schemes, which are summarized in Table 1 . The status of these protection schemes can be monitored from control center using their available data. Outage of above key elements can significantly affect the state trajectory of power system. On the other hand, divers control actions are available for normal and emergency conditions, but their coordination with aforementioned protection schemes is rarely considered. Therefore, the risk of loosing vital power system elements should be already considered/foreseen in the chosen control action in order to prevent occurrence of serial outage of network determinant resources. Hence, in order to achieve a reliable and effective control decision, two key requirements should be met:

Table 1
Protection schemes of power system equipment monitorable from control center.

	Transmission line	Synchronous generator	Nonsynchronous generator	Transformer
OC	✓			✓
UF		✓		
OE		✓		✓
LV			✓	
UV	✓			✓

Over current (OC), under frequency (UF), over excitation (OE), low voltage ride through (LVRT), under voltage (UV).

1. Preventive countermeasures: Preserving integrity of whole power system by preventing cascading outages;
2. Issuing proper control actions to settle the state variables in range.

2.1. Over current (OC) protection

For mathematical formulation of proposed method, a network with r branches ($T_k \in \{T_1 - T_r\}$) and b Buses (B_i, $B_j \in \{B_1 - B_b\}$) is considered. Fig. 1 indicates a typical bus-branch configuration considering power flow direction regardless of existing electrical elements in the branches (transmission lines or transformers). L_i and L_j represent the loads connected to the buses i and j, respectively.

The Incident Matrix ($M(t)$) describes the network topology, i.e. the connection between buses and branches including the power flow direction. $M(t)$ can be determined as below:

$$M_{b\times r}(t) = \begin{array}{c} \vdots \\ i \\ \vdots \\ j \\ \vdots \end{array} \overset{\begin{array}{ccccc} 1 & \dots & k & \dots & r \end{array}}{\begin{bmatrix} \dots & \dots & 0 & \dots & \dots \\ \dots & \dots & +D_k(t) & \dots & \dots \\ \dots & \dots & 0 & \dots & \dots \\ \dots & \dots & -D_k(t) & \dots & \dots \\ \dots & \dots & 0 & \dots & \dots \end{bmatrix}} \tag{1}$$

where $D_k(t)$ represents the power flow direction of branch k at time t and can be calculated based on direction of active power, i.e. $P_k(t)$:

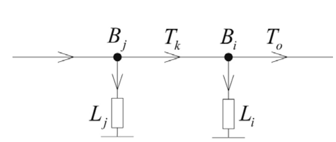

Fig. 1. Typical bus-branch topology.