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Reducing excessive standing phase angle differences: A new approach based on OPF and wide area measurements

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ABSTRACT

Power system restoration is a complex and vital task, which can be viewed as the repeated reconnection of de-energised elements of the network in blackout to re-energise them. However, the restoration process will be delayed if an excessive standing phase angle difference (SPAD) is detected across lines, and any delay in the restoration increases its economic and social costs. This paper proposes a two-step method for reducing excessive SPAD. In contrast to conventional techniques, this new approach optimally reschedules the machines to reduce the excessive SPAD, whilst avoiding abrupt changes in power output, and uses real-time information that enables operators to perform restoration in real-time. The method is tested using the IEEE 118-bus test system, and the results demonstrate that it can quickly determine a solution that decreases excessive SPADs to values below a user-defined threshold, whilst reducing operational cost and requiring changes in the power output of machines smaller than a given percentage of the nominal power output.

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Introduction

Power system restoration (PSR) aims to restore networks affected by partial or complete blackouts as quickly and safely as reasonable [1]. It is usually divided into three stages – preparation, system restoration, and load restoration [2]. Transmission lines are energised during both the system restoration stage, to restore the skeleton of the system, and the load restoration stage, to pick up as much load as possible [1,2]. Operational constraints must be considered when energising a line during any of these stages [2]. For example, the standing phase angle difference (SPAD) between the buses to be reconnected must be smaller than a given threshold, which is selected according to grid codes, voltage level and restoration practices [3].

During transmission loop closure operations (i.e., when closing lines), operators frequently detect large SPADs that must be reduced before closing the applicable circuit breaker (CB); this is particularly commonplace during the load restoration stage [3]. Excessive SPADs may be detected when reconnecting a line within a system or a tie-line between two subsystems [4–15]. Closing a line across a large SPAD will shock the network, and may cause power swings, high currents, voltage drops, unnecessary operation of system protection, or even the recurrence of the outage [16]. For this reason, the synchro-check relay in the CB will not allow it to be closed if an excessive SPAD is detected [7]. Therefore, the reduction of an excessive SPAD is a necessity if the line is to be closed.

The restoration of several power systems has been significantly delayed by excessive SPADs preventing the closure of CBs [17]. More recently, excessive SPADs across open tie-lines caused several unsuccessful re-closure attempts and delayed system restoration in the interconnected European Network (formerly UCTE) after excessive power flows on certain lines had caused it to separate into three electrical islands [18]. These, and other events with similar characteristics [19,20], clearly highlight the need to develop new techniques that can offer effective assistance to help operators when reducing large SPADs and accelerate the restoration process.

Two main approaches for reducing excessive SPADs are generation rescheduling and load adjustments [4–12]. These can be implemented on a trial and error basis, i.e., creating small changes in the generation schedule [4–9] or load levels [10–12] (mostly by picking up unserved load) and then monitoring the change in the SPAD. However, this approach is very time consuming and will undoubtedly result in considerable delays in the restoration process. Furthermore, the use of load adjustments is the last resort for most utilities [21], as it tends to result in the disconnection of customers, reducing thus the reliability indices [12].

The existing methods for reducing SPADs are based on heuristic analysis, mathematical programming and artificial intelligence

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[4–12]. These methods predominantly use the rescheduling of active power generation to create the desired change in the SPAD. However, some drawbacks do exist: a dependence on off-line processes, complex algorithms with long computation times, difficulties in implementation, a reduction in generator rotor shaft impacts (RSIs) without ensuring the necessary reduction in the SPAD, disconnection of load-blocks, and a lack of real-time information from Phasor Measurement Units (PMUs).

The lack of real-time information is particularly critical given the current use of PMUs to support Wide Area Monitoring System (WAMS) applications. PMUs can measure voltage and current phasors and frequency information across the system, all synchronised with high precision to a common time reference provided by a Global Positioning System [22], thus providing attractive solutions to many problems in modern networks. PSR following a blackout can largely be facilitated by the development and deployment of WAMS [23,24].

This paper proposes a two-step method that uses generator rescheduling to reduce excessive SPADs without exposing generators to RSIs. In the first step, an optimisation problem (i.e., a new optimal power flow, OPF, algorithm) to find the optimal generator schedule that will reduce the SPAD to within a user-defined threshold is solved. In the second step, the optimal way to implement this rescheduling without exposing generators to the abrupt changes in active power output that are associated with RSIs is determined. The proposed method uses information from WAMS to obtain real-time information about the voltage phase angle at both terminals of the line to be closed. Information from WAMS is also used to constantly measure the SPAD across lines and to confirm that the power changes undertaken in the second step (i.e., the implementation of the solution found by the OPF) has had the expected effect. This will then enable the operators to send a binary command signal to close the CB when the SPAD is below the defined threshold.

This paper is organised as follows. Section "SPAD and the Application of WAMS" defines the concept of SPAD and illustrates how WAMS can be used to support operators during the reduction of large SPADs. Section "Primal-Dual Interior Point OPF Algorithm" describes the OPF formulation and the electrical constraints that are included in it. Section "Proposed Method for Minimising the Operational Cost of Reducing SPADs" details the two-step method, and its effectiveness is demonstrated in Section "Simulation results". Section "Conclusions" concludes this paper, and provides some avenues for future work.

SPAD and the application of WAMS

This section extends the definition of the SPAD and describes an application of WAMS during restoration.

Standing phase angle difference

It is common practice for system operators to first close the CB at one end of the line to be reconnected during a transmission loop closure operation [21]. For example, in Fig. 1 it is considered that the CB at bus j is closed first when the transmission line i–j is to be energised. Therefore, the SPAD would be measured across the CB that remains in the open position (i.e., the CB at bus i). Accordingly, the SPAD across an open CB can be represented as the difference between the voltage phase angles at the line terminals as follows:

$$|\theta_i - \theta_j| \tag{1}$$

where θ_i and θ_j are the voltage phases at buses i and j, respectively (see Fig. 1).

The largest SPAD that a power system can withstand during the closure of a CB is determined using both steady-state and dynamic studies [3,6,7]. However, this maximum value mainly depends on the voltage level [3]. Therefore, three different values are employed worldwide: 20° for extra high voltage lines (i.e., 400 kV and above), 30–40° for 230 kV lines and 50–60° for 132 kV systems [3].

Application of Wide Area Monitoring Systems during PSR

Fig. 1 shows the envisaged application of WAMS to the reduction of excessive SPADs [16]. PMUs can be used to measure the voltage phase angles at both line terminals, which can then be used to calculate the SPAD across the line to be closed and check if the applicable value is greater than the predefined threshold.

Primal–dual interior point OPF algorithm

This section describes the OPF algorithm used in the first step of the new method (formally introduced in Section "Proposed Method for Minimising the Operational Cost of Reducing SPADs").

Definition and power flow equations

The network during restoration is modelled here using the set N_b of all buses, the set N_S of all buses but the slack bus, the set N_g of generator buses and the set N_l of load buses. The set of all buses directly connected to bus $i \in N_b$ is represented by the set $N_{b,i}$. From this, a set of ordered index pairs β that describe the sending-end (i) and receiving-end (j) buses of all branches in the system can be defined as follows:

$$\beta := \{(i,j) | i \in N_b, j \in N_{b,i}, \text{ and } j > i\} \tag{2}$$

The set of the sending-end and receiving-end buses of the transformers with load tap changers is defined as N_τ. The size of any set is described by its cardinality $|\cdot|$, e.g., the number of buses in the network is represented by $|N_b|$. Moreover, the (complex) bus-voltage at bus $i \in N_b$ is expressed using polar coordinates ($\widetilde{V}_i = V_i \angle \theta_i$). Therefore, the voltage phasors at each bus can be described using $\mathbf{V} \in \mathbb{R}^{|N_b|}$, which contains the voltage magnitudes, and $\boldsymbol{\theta} \in \mathbb{R}^{|N_b|}$, which consists of the voltage phase angles.

For a given voltage profile and network topology, the active (P_i) and reactive (Q_i) power injection at the bus iN_b are respectively computed as follows:

$$P_i(\mathbf{V},\boldsymbol{\theta},\mathbf{t}) = V_i^2 G_{ii} + \sum_{\substack{n=1\\ n\neq i}}^{|N_b|} [V_i V_n G_{in} \cos(\theta_i - \theta_n) + V_i V_n G_{in} \sin(\theta_i - \theta_n)] \tag{3}$$

$$Q_i(\mathbf{V},\boldsymbol{\theta},\mathbf{t}) = V_i^2 B_{ii} + \sum_{\substack{n=1\\ n\neq i}}^{|N_b|} [V_i V_n B_{in} \cos(\theta_i - \theta_n) + V_i V_n B_{in} \sin(\theta_i - \theta_n)] \tag{4}$$

where G_{ij} and B_{ij} are the ij-th elements of $\mathbf{G} \in \mathbb{R}^{|N_b| \times |N_b|}$ and $\mathbf{B} \in \mathbb{R}^{|N_b| \times |N_b|}$, respectively. The vector $\mathbf{t} \in \mathbb{R}^{|N_\tau|}$, with elements t_{ij}, represents transformer tap settings (implicit in $\mathbf{G}$ and $\mathbf{B}$).

The active (P_{ij}) and reactive (Q_{ij}) power flows in the branches are respectively calculated as follows:

$$P_{ij}(\mathbf{V},\boldsymbol{\theta},\mathbf{t}) = t_{ij}^2 g_{ij} V_i^2 - t_{ij} V_i V_j [g_{ij} \cos(\theta_i - \theta_j) + b_{ij} \sin(\theta_i - \theta_j)] \tag{5}$$

$$\begin{aligned} Q_{ij}(\mathbf{V},\boldsymbol{\theta},\mathbf{t}) = {} & t_{ij}^2 \left(b_{ij} + b_{ij}^{sh}\right) V_i^2 \\ & - t_{ij} V_i V_j [g_{ij} \sin(\theta_i - \theta_j) - b_{ij} \cos(\theta_i - \theta_j)] \end{aligned} \tag{6}$$

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