Electric Power Systems Research 88 (2012) 64–68

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Contingency analysis using synchrophasor measurements

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ARTICLE INFO

Article history:
Received 22 October 2008
Received in revised form
21 November 2011
Accepted 7 January 2012
Available online 28 February 2012

Keywords:
Contingency analysis
Synchrophasor
Phasor measurement units

ABSTRACT

This paper presents a new algorithm, using phasor measurements, that allows real-time analysis and correction of contingencies in power systems. The focus is specifically on overloaded lines. Contingency indicative phasor limits are investigated using current magnitude and voltage angle. These limits are applied to a rotating phasor chart. An algorithm which predicts sensitivity is applied to an off-line system in order to determine the buses that need to be monitored. An online system with available phasor measurement unit (PMU) data is used to verify the phasor chart obtained using off-line data. The chart is completed for on-line PMU data, and compared with the off-line chart for further verification.

1. Introduction

One of the most important aspects of power system operation is manipulating the network to supply the power demands of all loads efficiently. During daily periods of high demand, loading of the network peaks. This can cause the power flow on lines to increase, driving the line to run in overloaded conditions. One outage can cause power flow to redistribute within the network and may overload transmission lines as a consequence. Certain lines within the system are very sensitive to changes in power flow, these are critically loaded, but others may be able to handle excess flow. In many cases forcing outages of specific lines within the system will properly redistribute power flow in these more lightly loaded lines and allow alleviation of the overload while still supplying the power demanded by all loads. Phasor measurements are examined within large scale systems both pre- and post-contingency. Load flow is observed in an off-line system and a predictive phasor pattern is determined using the phasors at each bus in the system. The pattern is then tested against online phasor measurement unit (PMU) data of a large scale system provided by a local utility for verification.

The importance of finding a predictive pattern in phasor measurements for an online system lies in the time needed to analyze contingencies in the system. Current practice is to run a load flow on the system whenever a contingency occurs to identify any problems that may have been introduced. These load flows are not suitable for online applications because the power flow calculations depend on state estimators, which normally take minutes to update snapshots of the power system [1]. This is more than enough time for the system to collapse while waiting for a solution. PMUs, on the other hand, along with high speed communications networks make it possible to create wide-area monitoring systems that can update a snapshot of the power system within as little as one second [2,3]. This allows for much faster correction of any problems created by overloads or contingencies.

The phasor data in this case comes from PMUs installed at selected buses. PMUs are power system devices that provide synchronized measurements of real-time phasors of bus voltage and line currents. Many PMUs are currently installed in systems around the world for various applications [4]. Phasors, in general, are currently being greatly researched in the power industry. Phasors seem to give a good indication of system state in many different areas, and are being used in security [4], to create voltage stability limits [1], in state estimation [5,6], and many other applications including model validation [7], system monitoring [8], fault recording [7], and control and protection [9–11].

This paper determines a new method for contingency analysis. In Section 2 an off-line study is performed to determine which phasors are most indicative of overload. From these phasors, a predictive pattern is found to apply to limit thresholds. An operator display is proposed using a rotating pie chart. In Section 3 a new sensitivity equation is proposed and tested off-line in different loading conditions. Section 4 investigates the applicability of the pie chart to an on-line system with PMU data. This data includes a three-phase bus fault. The on-line system is reduced for analysis, and the reduced system is compared and verified using PMU data.

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0378-7796/$ – see front matter
doi:10.1016/j.epsr.2012.01.002

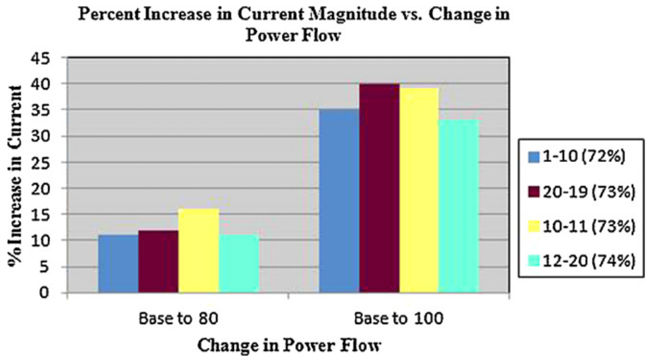

Fig. 1. % increase in $|I_{ij}|$ for lines around 73% capacity.

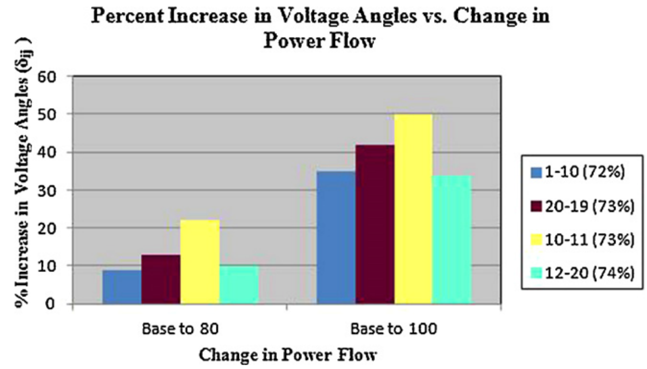

Fig. 2. % increase in δ_{ij} for lines around 73% capacity.

It is determined that limit thresholds for the pie chart could be created in the on-line system if the given system was operating in a heavier loading condition. In Section 5, the sensitivity equation is applied to the on-line system and consistency is examined. Section 6 provides comparisons between the off-line and on-line data, and Section 7 concludes the study.

2. Off-line study

The off-line system analyzed in this paper is a 37-bus system with a base of 138 kV, 100 MVA. All bus and line data is specified. The system is simulated using PowerWorld simulation software. This software is chosen above other simulators for its user interface and data configurations. The base case is built and all voltage and line capacity constraints are verified. Phasor measurements are taken at all buses in the base case loading condition and after the overall system load is increased by 20% (maximum allowable). A load increase of 25% forces some lines to operate above 100% of their capacity, which is not allowed. In the maximum allowable load increase condition, six lines are operating between 80% and 100% capacity, which is allowed for short periods of time during heavily loaded conditions. These six lines are observed before and after overload to determine a pattern in phasor measurements which allows limit setting.

This limit indicates when a line is crossing from a permissible capacity to an overloaded capacity. Specifically, the limits observe when a line crosses both 80% and 100% capacity thresholds. The percent increase limits in voltage angle difference (δ_{ij}) and current magnitude ($|I_{ij}|$) are found to give the most consistent pattern. The percent increases are found using Eq. (1)

$$\%\ \text{inc} = \left| \frac{(x_{\text{capacity}} - x_{\text{initial}})}{x_{\text{initial}}} \times 100 \right| \qquad (1)$$

Voltage magnitude, current angle, and real power are all observed, and determined to be inconsistent. To obtain the limits, voltage angle and current measurements are taken at the initial line loading condition. The system is then manipulated until the selected lines are operating at 80% capacity and 100% capacity. The percent increases from the initial capacity to 80% and from the initial capacity to 100% are calculated. The results are shown in Figs. 1 and 2 for lines operating around 73% initial capacity. Clearly a limit can be set, as the largest base capacity to 80% capacity is smaller than the smallest base capacity to 100% increase. Similar charts are created for lines operating at different initial capacities (all > 60%), and an average limit is found over the system.

Once the limits are established for the system, an interface is created to allow the operator to observe the limits and violations. The proposed pie chart is shown in Fig. 3.

The current and voltage angle limits must work jointly to indicate overload, meaning both limits must be reached for the line to cross the overload threshold. For this reason, the operator display will consist of two pie charts, one for voltage angle, and one for current magnitude. These pie charts provide the operator with the proximity of a line to overloaded operation.

3. Steady-state sensitivity analysis

Sensitivity analysis methods are very important when analyzing a large power system. Systems with older protection schemes may not have PMU data available at all locations in the system. Sensitivity methods help to determine the most efficient placement of PMUs. Newer protection devices come equipped with the ability to obtain phasor measurements. Now data processing, rather than location, is an issue. Multiple phasor measurements are taken by each PMU. If many PMUs are located in the system, the amount of resulting data will be enormous. Operators need an efficient way to process only the data that correlates strongly to system state. This reduces both the communication required, as there is less data to move from the PMU to the operator, and also the time necessary for data evaluation.

The equation for determination of sensitivity in this paper is developed using a premise from the previous section. The current magnitude and voltage angle are shown to be good indicators of system state, and are therefore used in determining the sensitivity to overload as well. The final sensitivity equation uses the partial derivative of the line current with respect to the line voltage angle difference, as shown in Eq. (2). The proof of this equation is shown in the appendix.

$$\frac{\partial |I_{ij}|}{\partial \delta_{ij}} = \frac{V_i V_j \ \sin(\delta_{ij}) \times |Y_{ij}|}{\sqrt{V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_{ij})}} \qquad (2)$$

Eq. (2) is applied to the off-line system for verification and the results are shown in Table 1.

As this equation represents a scaling factor, lines above 100 are determined to be sensitive. Table 1 shows consistency in the determination of sensitive lines in different loading conditions.

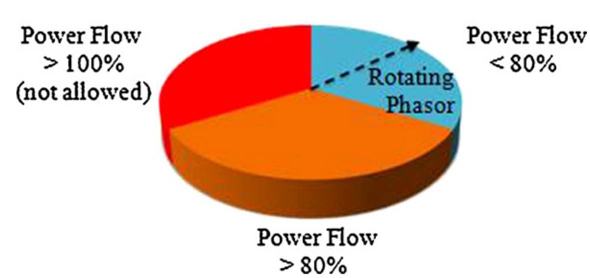

Fig. 3. Generalized rotating phasor pie chart.