ALLOCATION OF POWER QUALITY METERS FOR VOLTAGE SAG ESTIMATION USING EVOLUTIONARY ALGORITHMS

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ABSTRACT

Voltage measurements in specific buses of the power system during events of voltage sags and swells might allow for the estimation of short duration voltage variation (SDVV) in buses where power quality is not monitored.
The implementation of SDVV estimation relies on developed methods that make use of a least square error approach by comparing measurement data and simulated results so as to identify the event characteristics, e.g. fault location, fault type and fault impedances.
The number of power quality meters and the best way to allocate them along the transmission system is dependent upon the electric network.
This paper shows a method for the allocation of power quality meters, evaluating detection and estimation failure rates. In order to determine the best power quality meter allocation for a reliable voltage sag and swell estimation, one could think of an exhaustive search technique. This approach can be applied to small systems (few buses), but is unviable for real transmission systems, since the number of possible combinations of power quality meters is extremely high.
Amongst the many optimization techniques applicable to this problem, evolutionary algorithms have proven as a very good alternative. The fitness function was carefully formulated to assess how each possible power quality meter allocation will behave for the estimation and monitoring of voltage sags and swells.
The proposed algorithm was implemented and applied to a real transmission network. Some preliminary results are illustrated in this paper.

ESTIMATION OF SHORT DURATION VOLTAGE VARIATIONS (SDVVS)

The estimation of voltage sags and swells consists in a method to determine mainly their magnitude and duration in buses where there is no power quality meter. Also, this method allows for the estimation of the expected number of events (frequency) in a specific bus in a given period [1,2], by having a power quality monitoring system, where meters are installed in some specific buses. The proposed estimator [1] for transmission and subtransmission systems makes use of measured voltage values. The main steps in this estimator are described as follows.

Monitors data processing: this phase deals with the interface between the power quality (pq) monitors and the estimation module. From the main measured data, it is possible to evaluate the main parameters that characterize SDVVs. The instantaneous voltage records are the most important source of data, although RMS values recorded in short intervals, e.g. for every cycle, can be used for estimation methods. The pq monitors are usually triggered to capture current and voltage waveforms by selected parameters, usually overvoltage or undervoltage thresholds. The main parameters evaluated to be used by the estimation method are the voltage magnitudes for the fault period. Durations of the events can also be determined, for the SDVV characterisation.

Network data base and Electric calculations: a data base is formed by the electrical network information (configuration, electric data, etc.), which is used by power flow and short circuit calculation modules. The load flow module evaluates the voltage and current profiles in steady state conditions, that is prior to the events. Such profiles are used as an input for the short circuit module, that aims at:

- obtaining the short circuit conditions for faults (various types of fault) in all network buses and the corresponding phase voltages at each monitored site. The results of such simulations are stored in a specific data base which is accessed by the fault location module.

- estimating SDVV values in selected buses once the fault location is determined.

For instance, considering a three phase fault, the voltage at a generic bus *k* for the fault position *f* is given by:

$$v_{k,f} = v_{prefault(k)} - \frac{z_{kf}}{z_{ff}} \cdot v_{prefault(f)}$$

where $v_{prefault(k)}$ and $v_{prefault(f)}$ are previous to fault voltages at *k* and *f*, respectively, z_{kf} is the transference impedance between *k* and *f*, and z_{ff} is the Thévenin impedance at point *f*.

Fault location: by making use of the preliminary analysis and the simulation data base, the fault location method is based on the least square method. Once the fault is located and characterised, the SDVVs can be evaluated in the selected sites, which constitute the so called virtual measurement data base. The least square method is applied to the monitored sites, that is, the fault location that provides the least sum of squared errors between the measured and simulated voltage values is to be chosen. This method leads to the fault location as well as identification of the fault type (three-phase, single-line-to-ground, line-to-line, double-line-to-ground). By considering a given fault (type *f* and location *j*), the squared error for a monitored site *i*, $[\delta_i]_{f,j}^{\;2}$, is given by the following equation:

$$[\delta_i]_{f,j}^{\;2} = \left(\left| Va_i^{mes} \right| - \left| (Va_i^{calc})_{f,j} \right| \right)^2 + \\ + \left(\left| Vb_i^{med} \right| - \left| (Vb_i^{calc})_{f,j} \right| \right)^2 + \left(\left| Vc_i^{mes} \right| - \left| (Vc_i^{calc})_{f,j} \right| \right)^2$$

Determination of voltage variations: once the location and type of the fault are determined by the least square method, SDVVs can be evaluated for the buses where one is interested.

POWER QUALITY METER ALLOCATION

In order to establish a reliable SDVV estimation, the number of power quality meters must be allocated in a optimal way along the transmission system. This allocation relies on some power system characteristics, such as network configuration, line impedances, transformer impedances and connection types, voltage levels, etc. The search for an adequate pq meter allocation can not be carried out in an intuitive way, specially for large networks. Normally there are not sufficient measurements related to voltage sags and swells to be used as an input for the allocation method. Thus, it is more convenient to utilize fault simulations to analyse voltage values throughout the monitored and non-monitored systems.

Uncertainties in the assessment of SDVVs

As mentioned above, the estimation algorithm relies on the monitoring of some specific buses when faults occur in the system. Then the estimation algorithm determines voltage variations in some given buses. However, some conditions must be met so that the accuracy in the estimation is reasonable enough. More than a fault point can provide similar measured voltage values in the monitored buses, due to the following factors:

a) possible differences between the estimated voltage and the measured voltage in the monitored points, due to uncertainties e.g. in network models, measurement, fault impedances, topology information, etc.

b) different fault locations might be determined due to the network configuration, when similar voltage values result in monitored buses, though the voltage values in the estimated sites might differ, as shown in Fig. 1.

Due to uncertainties related to the voltage computations in fault conditions, one might admit a deviation $\pm\delta$ between the computed voltage values V_{calc} and the measured voltage values V_{meas} in the monitores sites.

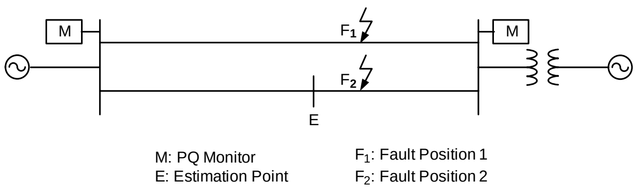

Fig. 1 – Two different fault locations producing the same voltage values at the monitored sites and different voltage values at the estimated site (E)

If a voltage sag registers a voltage $V_{k,meas}$ in a monitored site *k*, a set of fault locations might incur in a computed voltage $V_{k,calc} = V_{k,meas} \pm \delta$; this means that within a tolerance different fault locations might lead to the same voltage value. That is, different voltage estimations can be computed according to what fault location is chosen, and consequently different deviation values ε for the estimated voltage with respect to the real voltage that would occur at that site.

If one makes use of a number of monitors in adequate sites, one can reduce the set of multiple fault locations that lead to the same computed voltage values. This procedure reduces the ε deviation for the estimated sites.

Evaluating the estimation uncertainties

By considering what was exposed in the previous item, uncertainties involved in SDVV estimation depend on the propagation characteristics of SDVVs during fault conditions and pq meters allocation. In order to evaluate the corresponding uncertainties, the following procedure was established to determine the possible deviations that might exist in the voltage values estimation. The evaluation is undertaken for voltage sags, though it can be extended for voltage swells as well.

- A number of control points is specified, which correspond to the sites where one needs to assess SDVVs, either by measuring or estimating;
- Control points with no pq meter are considered as estimation points;
- For a given fault type, voltage values in control points are obtained for all possible fault locations (system buses and along the lines);
- For each fault location, one verifies whether the voltage at an estimation site is lower than a threshold for voltage

sags (normally 0.9 pu); if such a case does not occur, there is no interest in the estimation;

- A detection failure must be checked, that is, whether at least one pq meter detects the fault (the event must trigger the event capture function of the pq meter when the threshold is reached);
- If there is no failure in detection of the event, the voltage at monitored sites are checked;
- Taking the computed voltage values at the monitored sites for each fault location as reference, one must check whether some other fault locations lead to the voltage values with differences inferior to a specific maximum deviation (e.g. 5%).
- If this is not the case, the fault location does not lead to ambiguity and zero deviation is assigned to such voltage estimation;
- However, if this is the case, i.e. more than a possible fault location leads to similar voltage values at the monitored sites, the ε deviations, as previously defined, are then determined for each estimation site. In each estimation site, the maximum deviations ε are stored, considering other fault locations. The maximum deviation amongst all estimation sites is then determined.
- Once all fault locations are computed, the obtained values are classified according to their maximum ε deviations in order to obtain the occurrence frequency with respect to the deviations (in % of the rated voltage). The following ranges were considered for the classification: 0 to 5% deviation, 5 to 10% deviation and deviations greater than 10%;
- If a 5% uncertainty with respect to the rated voltage is assumed as adequate, one should come up with maximum deviations at the estimation sites in the range from 0 to 5%. However it is reasonable to accept maximum deviations in the range 5-10% to be tolerated whereas maximum deviations above 10% would be not acceptable.

Applying the estimation uncertainty concept to the pq meter allocation in a transmission system

As seen in the previous items, the proposed method allows for the determination and classification of possible deviations in voltage values estimated. Such approach was implemented in a computer program that takes as input the voltage values in system buses for faults in different locations. Such input data file is a matrix where the columns correspond to the control buses and the lines the fault locations. Such matrix is created by a fault analysis program. The detection failures and possible estimation deviations are evaluated as a function of the pq meter allocation alternative that one needs to assess.

In order to obtain better allocation alternatives for the estimation of SDVVs, allocation vectors are created, to indicate those buses where the monitors should be installed. Each allocation vector is submitted to the proposed procedure, thus determining detection failures and possible deviations in the estimated voltages. Two main indices are then determined:

- detection failure rate

- voltage estimation failure rate

The detection failure rate is determined by the number of cases, amongst the possible fault locations, for which a estimation bus experiences a voltage sag but no pq monitor detects the fault. This rate is given as a percentage of the total number of considered fault locations.

The proposed criterion to determine the voltage estimation failure rate bases upon the maximum possible voltage deviation (ε) that an estimation point might exceed 10% of the rated voltage. The estimation failure rate is given by the relation between the number of cases in which the deviation in any estimation point exceeds 10% and the total number of fault locations.

The ideal situation is that one where both failure rates are null. However, low values for these failure rates (e.g. 5%) are tolerable to the estimation of power quality indices in a power system.

The alternative allocations to be studied are generated by using an adequate search algorithm. Failure rates are evaluated for each alternative, so that the best allocation bearing the minimum power quality monitors is selected.

Search algorithm for pq meter allocation

In order to determine the best power quality meter allocation for a reliable voltage sag and swell estimation, one could think of an exhaustive search technique. This approach is simply applied to small systems (few buses), but unfeasible for real transmission systems, since the number of possible combinations of power quality meters is extremely high.

Amongst the many optimization techniques applicable to this problem, evolutionary algorithms have proven a very good alternative, specifically the genetic algorithm [4]. In this technique, the process starts with an initial population and orders the elements of this population according to the fitness function. A new population is then generated according to genetic operators (cross-over, mutation, elitism, etc.) and the process evolves for a given number of generations that allows for convergence.

In the present application, the fitness function must be carefully formulated to assess how each possible power quality meter allocation will behave for the estimation and monitoring of voltage sags and swells. The string codification, a very important characteristic of the evolutionary technique, must also be implemented in an effective way that improves the convergence of the method.

Concerning the SDVV estimation, a minimum number of pq monitors is searched so that the detection and estimation failure rates are within acceptable ranges. Two evaluations are then carried out to assess the tolerance levels with respect to the detection and estimation failure rates:

a) detection and estimation failure rates equal to zero;

b) detection and estimation failure rates lower than 5%.

This analysis can be realized either for the case in which all system buses are considered as control points or for the case of selected control points.

Preliminary studies indicate that possible savings in pq monitors by using this approach are dependent upon the characteristics of SDVV propagation in the faulty network and upon the estimation sites. When all the systems buses are to be estimated, the method can result in considerable savings.

System faults triggering few pq monitors (one or two) show hard SDVV estimation, since the savings in pq monitors are small.

Application of the method to a transmission system

The proposed algorithm was implemented and applied to a real transmission network, which is part of the Brazilian interconnected power system. This subsystem consists of 154 buses in different voltage levels (500 kV, 345 kV, 230 kV and 138 kV). A total of 2300 fault locations were considered (each power line was divided into 10 branches).

In this preliminary evaluation, only phase-to-ground faults were considered, since this fault type is predominant. Amongst the 154 buses, only 30 buses were selected as control points, i.e. where pq indices should be determined. The following results were obtained:

a) For failure rates equal to zero, 26 pq meters are needed, what represents 13% savings regarding the number of meters;

b) Considering the case for failure rates no greater than 5%, 19 pq meters should be installed, representing 37% savings;

When all system buses are considered as control points, the economy is expected to be higher. It was observed that the considered transmission network presents unfavorable SDVV propagation characteristics from the point of view of SDVV estimation, since the faults are generally “seen” only by the buses closer to the fault points. Some additional evaluations related to another network, namely a sub-transmission system with predominantly radial configuration, indicated more substantial savings in pq monitors.

CONCLUSIONS

This paper shows a method for the allocation of pq monitors, considering estimation of SDVVs in electric power systems.

The evaluation is effected by determining the possible detection and voltage estimation failure rates as a function of each alternative of monitor allocation.

The optimal pq meter allocation is determined by an evolutionary algorithm that minimizes the detection and estimation failure rates and the number of installed pq meters.

Preliminary cases indicate possible savings in pq monitoring systems by the application of the proposed methodology. However, results are dependent upon the network characteristics (propagation of SDVVs in the system during fault conditions) and the sites where the SDVVs should be monitored. When just few buses are to be monitored, the savings might be relatively smaller.

As further developments the research team is working to improve the evaluation model, by using different failure rates in lines and buses, different fault types with corresponding probabilities of occurrence, amongst others.

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