AN EFFICIENT DETERMINATION OF VOLTAGE SAGS FROM OPTIMAL MONITORING

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ABSTRACT

This paper presents a method to estimate the sag performance at non-monitored buses of a transmission system based on limited monitoring and stochastic assessment of voltage sags. An integer programming-based modelling is proposed for choosing the optimal locations of power quality meters. A branch-and-bound-type algorithm is used to solve the optimization problem. Optimization problem modelling and estimation of sag performance in non-monitored buses is made with high precision. The flexibility of the method has been increased by considering the fault positions on the lines as well as buses. The computer algorithm is applied to real transmission network and results show the method is successful.

INTRODUCTION

Voltage sags (dips) are sudden drops in the root mean square (rms) voltage, power quality disturbances that must be treated as a compatibility problem between sensitive loads and power supply [1],[2]. Such an approach requires a suitable description of the vulnerability of the load to voltage sags and of the performance of the network in terms of the expected number of events and their characteristics. In order to ensure compatibility, the sensitivity of the load to voltage sags and the expected performance of the system must be conveniently described and compared. Equipment sensitivity is usually presented by means of voltage tolerance or power acceptability curves like CBEMA [3], whereas system performance is usually described by means of site and system indices [4].
The performance of the network is described using tables or histograms. The information needed to complete such tables or histograms can be obtained either from simulation (stochastic assessment of voltage sags) or power quality monitoring programs. Monitoring of power supply is well accepted by engineers as a means of profiling power quality. However it is expensive, it requires long metering periods, and a large number of meters when the aim of the program is the characterization of an entire transmission system. Ideally, a full monitoring program should be used to characterize the performance of an entire system, i.e. every load bus should be monitored. Such a monitoring program is not economically justifiable and only a limited set of buses can be chosen for a monitoring program. This has led to the optimal monitoring program proposed in [5]. Optimal decisions regarding the number of meters and their locations are needed so that the number of meters is minimized without missing any essential information. This paper introduces an improved optimal monitoring program that identifies optimal locations of meters. First, analytical expressions for the calculation of voltage sag magnitude due to single phase faults at every point of a transmission system are derived. Then an integer programming model is introduced for minimizing the number of meters needed to characterize a transmission network in terms of voltage sags. After that, the results of the optimal monitoring program are used to obtain the voltage of buses not being monitored. In this paper, incorporating nodes as fault positions along the lines makes the modelling to be more precise. The optimization problem is solved using branch-and-bound type algorithm.
Fault positions were chosen so that no more than 1 km of line separated two near-fault positions. To achieve this, more than 1900 faults were simulated with MATLAB.
Single phase faults are considered and the effects of power transformers are taken into account. Comparison system indices obtained by applying this method and system indices obtained by the full monitoring program show the applicability of the method. A hypothetical full monitoring program can be obtained from stochastic prediction method based-on method of fault positions.

OPTIMAL MONITORING PROGRAM

A monitoring program is a particular arrangement of power quality meters or monitors in the network. In order to find an optimal monitoring program, the following two premises are considered. a) A minimum number of monitors should be used to describe the system performance in terms of sags. b) No essential information concerning the performance of load buses in terms of sags should be missed.
Hence, the optimization problem is formulated to minimize the monitoring cost subjected to coverage of the entire network. Optimal sag monitoring programs have been introduced in [5],[7] and are briefly reviewed here.
In this paper, to increase precision, the faults are considered to be on the transmission lines as well as busbars, i.e. analytical expressions for the calculation of voltage sag magnitude due to the faults at many point of a transmission system are derived. Then optimization problem will be formulated as a binary integer-programming problem.
The number of sags recorded at a site during a given monitoring time depends upon the critical threshold setting of the power quality monitor. The number of events captured by the meter can be explained from the growth of the exposed area (of the meter) with increasing sensitivity of the monitor. The monitor reach area is defined as the area of the network that can be observed from a given monitor

position. The monitor reach area of a monitor installed at a bus k is exactly the exposed area of that bus for the same voltage threshold. Short circuit faults inside the MRA will trigger the meter whereas faults outside will not. For a single site the monitor reach area can be described by a set of fault position indices pointing to components of the network where the occurrence of faults will cause triggering of the monitor. To describe all potential MRA a binary matrix is more convenient (1).

$$MRA_p = mra_{ij} = \begin{cases} 1 & if \quad V_{ij} \le p \\ 0 & if \quad V_{ij} > p \end{cases} \quad , \forall i, j \qquad (1)$$

Where v_{ij} is the residual voltage seen at bus i due to a fault at position j and p is the voltage threshold of the meters. Note that a particular row k of MRAp indicates (by means of 1) the fault positions that can be seen by a meter installed at bus k with a voltage threshold p. Similarly, column j of MRAp indicates the meter positions from which a fault at j can be seen.

In order to estimate the sag performance at non-monitored buses, a monitoring program must be designed so that the any potential fault triggers at least one power quality meter [8]. A minimum monitoring program that covers the entire network can be designed by solving the optimization problem (2).

$$\begin{aligned} & Min\left(\sum_{i=1}^{N} x_i\right) \\ & Subject \quad to: \qquad (2) \\ & MRA_p^{\ T}.X \ge b \end{aligned}$$

Where x_i is the binary decision variable indicating the need for a monitor at bus i, N is the number of potential monitor positions (actual buses of the power system). The right hand side vector b defines the level of redundancy of the monitoring program. A particular value of b_i indicates that a fault at the fault position i will trigger at least b_i monitors. The level of redundancy of the monitoring program is the minimum number of monitors that is guaranteed to trigger on the occurrence of a fault. The T over MRAp indicates transposition of the monitors reach area matrix for voltage threshold p. This matrix is determined with more precision than MRA was introduces in [5],[7]. To consider the fault positions on the lines as well as the fault positions on the busbars, the new nodes along the lines must be taken into account.

Elements of X are x_i as indicated in (3). The vector is referred as "monitor positions vector". A given value of the monitor positions vector indicates where the monitors should be installed.

$$x_i = \begin{cases} 1 & if \ a \ monitor \ is \ needed \ at \ bus \ i \\ 0 & otherwise \end{cases} \quad , \forall i \qquad (3)$$

A minimum monitoring program is one that makes sure that every fault triggers at least one monitor, i.e. the particular arrangement of monitors described by X = (x1,..xn) that solves (2) for b_i=1 for all i. In this paper, single-phase-to-ground faults, SLG, are used to design monitoring programs, which are then used to estimate the sag performance at monitored and non-monitored buses of a 41-bus system. In absence of actual measurements, simulated ones are used to contrast results from the estimation against pseudo-measurements.

The problem described by (2) is a binary (linear) integer optimization program, the solution of which minimizes the number of meters subject to the coverage of the entire network. Total enumeration is impossible for most problems as soon as the number of variables exceeds 30. The Branch and Bound algorithm is used in almost all optimization packages because it is an efficient way to deal with this kind of problem.

ALGORITHM FOR VOLTAGE SAG ESTIMATION

Voltage sag performance at non-monitored buses of a power system can be estimated by combining the monitoring results from a limited set of buses and the stochastic assessment based on the method of fault positions. We will call this procedure Voltage dip or sag estimation (VSE). Sag estimation is a method that makes it possible to estimate the residual voltage and the rate of occurrence of voltage sags at non-monitored buses. The estimation is based on monitoring and stochastic assessment. Next section presents a new approach for voltage sag estimation.

Finding potential fault positions

Method of finding PFP set has been introduced in [8] and is briefly reviewed here.

Consider the hypothetical network diagram shown in Fig. 1 where the 0.9 p.u. and 0.5 p.u. monitor reach area of bus 7 are shown. Inside the $MRA_{7(0.9)}$ seven buses (b1, b2, b3, b4, b5, b6 and M7) and six particular fault positions (fp1, fp2, fp3, fp4, fp5 and fp6) are depicted. Each fault position represents a limited length of line, and hence a fraction of the fault rate is assigned to each fault position. Suppose that a fault at an unknown position triggers monitor M7 and that a residual voltage 0.5 p.u. (± error) is recorded. From this limited information, a number of potential fault positions can be found (fp1, fp2, fp3, fp4, fp5, and fp6). Let PFP be the set of potential fault positions.

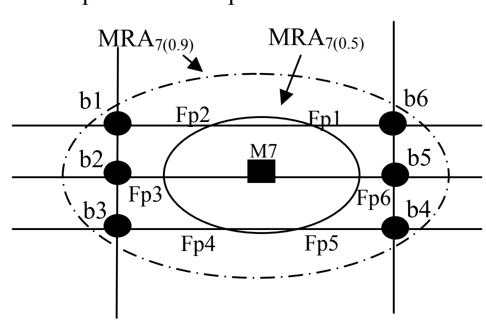

Fig.1. A simplified diagram of a part of a transmission network.

Then, PFP is formed by the indices corresponding to fault positions in the areas of the network where faults will result in a residual voltage similar to 0.5 p.u. at bus 7. Mathematically:

$$fp_i \in PFP \quad \Leftrightarrow \quad \begin{cases} fp_i \in MRA_{7(0.9)} \\ V_{7\,fpi} = 0.5 \pm \varepsilon \end{cases}, \ \forall i \qquad (4)$$

where fpi is the i-th fault position, $MRA_{7(0.9)}$ is the monitor reach area set of bus 7, V_{7fpi} is the residual voltage at bus 7 during a fault at the fault position i, and ε is a tolerance factor that takes into account uncertainties and errors. The information given by only one monitor does not allow finding the exact fault position however the residual voltage and the rate of occurrence at each non-monitored bus can stochastically be estimated as it will be shown.

Magnitude Voltage Sag Estimation

In the magnitude or event per event approach, only one residual voltage is assigned at each non-monitored bus per fault. The proposal is to calculate a weighed average residual voltage, the average calculated from all potential residual voltages, using the per-unit fault rate of potential fault positions as weighing factors. For example, (5) gives the unique residual voltage to be assigned to a general bus k of the hypothetical network in Fig. 1.

$$v_k = \frac{1}{\sum_{i=1}^{n} \lambda_{fpi}} \sum_{i=1}^{n} \lambda_{fpi} . v_{k\,fpi} \qquad (5)$$

where v_k is the estimated residual voltage at bus k caused by a fault at an unknown fault position, λ_{fpi} is the long-term fault rate of fault position i, n is the number of fault positions, and v_{kfpi} is the residual voltage at bus k caused by a fault at position i. Note that the application of (5) to bus M7 results in v_7 = 0.5 p.u., the value recorded at bus 7.

SIMULATION AND RESULTS

Fig. 2 shows the test system. It corresponds to the 41- bus Tehran Regional Electricity Company.

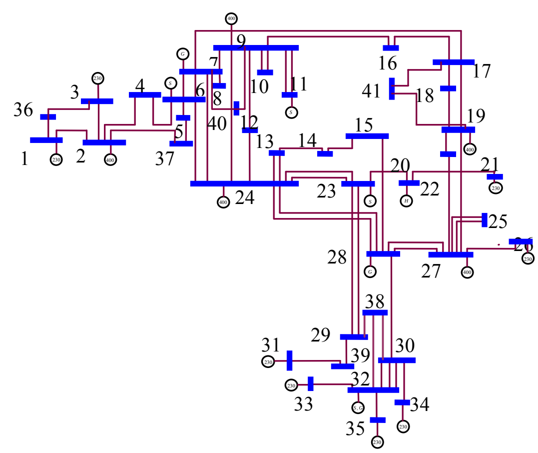

Fig. 2. Tehran Regional Electricity Company, 230 KV.

The fault rate for lines is assumed to be 0.0134 faults/year-km and to be the same for all lines. This factor is assumed to be 0.08 faults/year for all buses. The MRA matrix is built using 1954 SLG fault positions with a voltage threshold of 0.9 p.u.

In order to obtain a minimum-monitoring program, the level of redundancy b is set to 1. Branch and Bound search is used to solve (2) for a transmission system shown in Fig. 2. The monitor reach area matrix was built considering single phase fault positions at buses and lines for voltage threshold of 0.9 p.u. The optimization problem resulted in 41 binary decision variables with 1954 linear constrains. For a Voltage threshold of 0.9 p.u, six monitors were sufficient to cover the entire network. The optimization problem has multiple solutions in the sense that the minimum number of monitors (six for 0.9 p.u.) can be spread over the network in different ways satisfying the constraints. Table I presents six arbitrary selected optimal monitoring programs (OMP) in which the monitor positions are indicated. It can be seen that some buses are recurrently selected. For example, node 1 is contained in the six optimal solutions presented. Minimum-monitoring program is referred to as OMP; it requires 6 meters and guarantees that any single-phase-to-ground fault SLG triggers at least one monitor. This program can be selected from programs presented in table I.

Table I
Optimal monitoring programs for V<0.9

OMP1	OMP2	OMP3	OMP4	OMP5	OMP6
1	1	1	1	1	1
6	5	13	9	22	16
22	21	21	22	24	21
26	26	26	26	26	22
31	38	31	31	31	26
38	39	33	32	33	31

In order to test the proposed method, the monitoring program described above (OMP) should be implemented and one-year measurement results should be used to run the algorithm. Simulated measurements are used to test the method.

MVSE results

For an unknown fault position, the optimal monitoring program OMP recorded the information corresponds to table II. A single value of residual voltage can be estimated for each non-monitored bus by calculating the weighted residual average using the per-unit fault rate as weighting factors. This procedure makes it possible to estimate a unique residual voltage per fault. The magnitude voltage sag estimation gives unique residual voltage for each buses based-on monitors information, see Table III. Table III shows the residual voltages at all non-monitored buses during the SLG fault at an unknown fault position.

Residual voltages such as presented in table III are estimated for each unknown fault position.

Table II
Monitoring program information

Monitor no.	Bus no.	V (p.u.)
1	1	0.15
2	6	0.70
3	22	0.86
4	26	0.89
5	31	0.86
6	38	0.93

Table III
Estimated residual voltages of non-monitored buses

Bus no.	V (p.u.)	Bus no.	V (p.u.)
2	0	21	0.87
3	0.22	23	0.86
4	0.28	24	0.85
5	0.52	25	0.90
7	0.72	27	0.89
8	0.72	28	0.87
9	0.87	29	0.86
10	0.88	30	0.95
11	0.87	32	0.95
12	0.86	33	0.95
13	0.85	34	0.95
14	0.85	35	0.97
15	0.86	36	0.49
16	0.87	37	0.26
17	0.86	39	0.86
18	0.88	40	0.83
19	0.89	41	0.86
20	0.89		

Histograms can be obtained from estimated residual voltages for each unknown fault position. Fig. 3 shows the estimation method is a successful one in providing the statistics of all non-monitored buses. The small discrepancy between full monitoring program results and estimated performance is accepted since only 6 monitors are used to characterize the 41-bus system.

CONCLUSION

In this paper a method for finding fault positions and voltage sags of non-monitored buses has been presented. The fault position has been considered to be on both buses and the points on the transmission lines. A computer algorithm has been developed to find optimal monitoring positions and subsequently the voltage sags of buses. The algorithm has been applied to 41-bus Tehran Regional Electricity Company and the results show success of the approach.

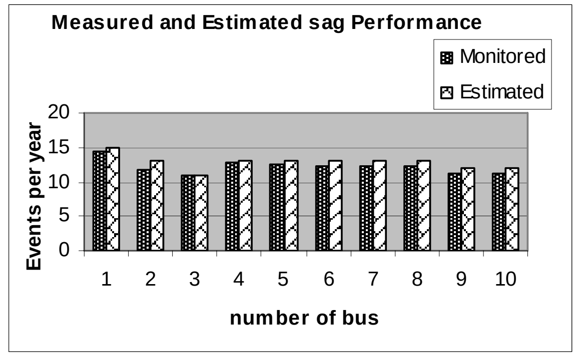

Fig. 3. Monitored and estimated dip-performance at 10 buses of system.

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