METHODOLOGY FOR FLEXIBLE, COST-EFFECTIVE MONITORING OF VOLTAGE SAGS

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ABSTRACT

This paper proposes a methodology to determine a range of monitoring programmes for estimating voltage sag performance in the network. The main advantages of the proposed method are its capability to handle any kind of user-defined voltage sag characteristics, and the possibility to adjust the accuracy of the estimation to find an acceptable trade-off between accuracy and the cost of monitoring programme. The proposed methodology results in allocation of sets of monitors that will register voltage sags with pre- specified characteristics at monitored buses, and estimate sag performance in the rest of the network with a pre-defined accuracy.

INTRODUCTION

The foreseen evolution of power systems will bring considerable investment in monitoring system infrastructure augmenting the number of installed intelligent electronic devices (IED). The development of fault location systems based on IED, such as power quality monitors, is anticipated as one of the most important components of advance distribution automation (ADA) [1]. The information collected by the fault-location system can be used for determining the grid impact of voltage sags. An example of such application is the optimal sag monitoring programme (OSMP), i.e. the minimum set of monitors required for estimating the voltage sag characteristics at non-monitored buses.

The optimal monitor placement method proposed in [2] determines OSMP that guarantee that all fault-induced sags will be captured by at least one monitor. Then, the sag characteristics at non-monitored buses are estimated by performing voltage sag simulations at the fault location estimates. Fault location estimates are determined using a voltage drop fault location technique. This fault location technique however, is susceptible to changes in, among others, fault resistance, fault position along lines, and pre-fault voltages.

A more robust fault location method is proposed in [3] and it is well suited for sag monitoring since it is based on the same network data as the voltage drop approach and utilizes limited voltage measurements. This method provides exact fault-location equations that are immune to fault resistance and fault position along lines. This fault location technique is incorporated in the proposed methodology.

PROPOSED METHODOLOGY

While the objective function of the optimal sag monitoring problem is to minimize the number of monitors subject to complete observability of short-circuit faults, the aim of the proposed approach is to jointly minimize the number of monitors deployed and the sag estimation error at non-monitored buses. The sag characterization of non-monitored buses is done by simulating faults at the fault locations estimated using the above-mentioned fault location method. The accuracy of the sag estimation is given by the difference between the real and the estimated number of sags.

Sag Estimation Accuracy Measure

The sag estimation accuracy of a sag monitoring programme (SMP) is defined here as the average absolute difference between the real and the estimated number of sags at the buses of the network. Voltage-tolerance curves such as CBEMA, voltage sag immunity standards like SEMI F47, performance indices like SARFI-X, or voltage-sag tables such as generalised sag table can be used to specify the type of sags (sag characteristics) that the monitoring programme will use for assessment of the accuracy of the estimation. For example, the sag estimation error (SEE) for voltage sags specified by SARFI-X indices is calculated as

$$SEE = \frac{\sum_{i=1}^{N} \left| SARFI\text{-}X_i^{rea} - SARFI\text{-}X_i^{est} \right|}{N} \tag{1}$$

where $SARFI\text{-}X_i^{rea}$ is the real number of voltage sags with magnitude equal to or less than X at bus i, $SARFI\text{-}X_i^{est}$ is the estimated number of sags with the same characteristics at bus i, and N is the total number of buses.

Monitor Placement

An iterative search strategy is introduced to determine SMP that minimize (1). At every iteration, the sag estimation error (SEE) at each bus is calculated and the location with the minimum error is chosen as the monitor location corresponding to that iteration. The gradual search is run repeatedly increasing the number of monitors and reducing (SEE) at each stage. The search is terminated when the SEE has been reduced to a pre-defined value or a pre-defined number of monitors have been placed.

APPLICATION

Sag monitoring programmes have been determined following the proposed methodology for a generic distribution system (GDS) and for voltage sags with different characteristics. The performance of the developed monitoring programmes and the OSMP where then compared. The GDS [4] used for the case studies comprises 275-kV transmission in-feeds, 132-kV and 33-kV (predominantly) meshed distribution networks, and 11-kV (predominantly) radial distribution network. The network has 295 buses, 278 lines (over-head lines and underground cables) and 37 transformers with various winding connections such as Yy, Dy, and Yd.

Symmetrical and asymmetrical faults are simulated at six points on every line of the system, two at 0.01 from each end of the line and four distributed uniformly between these two, i.e. a total of 1668 fault positions have been considered.

Voltage Sag Monitoring Programmes

The sets of monitors for registering voltage sags with characteristics specified by SARFI-90, SARFI-80, SARFI-70 indices, and SEMI F47 sag immunity standard have been determined. The real SARFI indices at all buses of the network have been calculated taking into account the voltage sags caused by all simulated faults.

In addition, the number of voltage sags falling in the equipment shut-down region of the SEMI F47 standard has been computed. The equipment shut-down region of the SEMI F47 standard was determined for the GDS according to the maximum fault duration times assumed in the study and presented in Table I. Such region is represented in Fig. 1 as the light-red-coloured area below the SEMI F47 curve between 3 and 15 cycles.

In brief, all sags with magnitude less than 0.5 p.u. and sags caused by faults occurring at the 11-kV system having a magnitude below 0.7, lie in the GDS equipment shut-down region. The aim of the sag monitoring programme obtained for the SEMI F47 is to minimize the SEE for this type of sags.

An iterative search was performed to find the set of monitors that reduced (SEE) to zero and the results are presented in Table II. It was found that, independently of the three SARFI indices used, ten monitors will determine the sag performance of the network with 100% accuracy, i.e. the average difference between the real and the estimated number of sags at all buses is zero.

Table I Fault duration times [5]

Voltage level (kV)	Fault clearing time (ms)
11	300
33	150
132	80
Bus faults	60

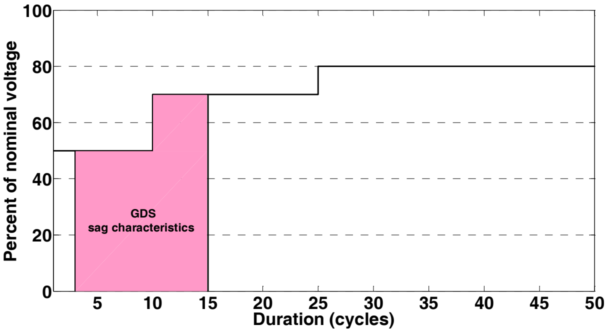

Fig. 1. SEMI F47 sag immunity standard and GDS equipment shut-down region.

However, as it can be seen in Table II, placing eight monitors in the network can reduce the average SEE to 8 or less sags. A greater reduction of the error in the estimation of sags (just 1 sag) is achieved with the same amount of monitors (8) if the standard SEMI F47 is used. In fact, one monitor less than the original 10 selected using SARFI indices, i.e., 9 monitors, is required to attain 100% accuracy in the estimation if standard SEMI F47 is used. Moreover, seven monitors can estimate the system sag performance averaging an error of only 3 sags.

Although the buses selected for monitoring can vary according to the SARFI index and the sag immunity standard SEMI F47, the number of monitors assigned to each voltage level of the network is the same for the four SMP: four monitors are placed at 11 kV, four at 33 kV, and two at 132 kV.

With the proposed methodology, monitor locations are selected gradually based on their contribution to reduce the sag estimation error, and therefore it is possible to calculate the distribution of the sag estimation error at each stage to provide a more detailed insight in the accuracy achieved with the addition of each monitor.

Table II Voltage sag monitoring programmes for several SARFI-X indices and SEMI F47 immunity standard

Number of monitors	*Monitor location (bus number)*				*Sag estimation error (E)*			
	SARFI-90	SARFI-80	SARFI-70	SEMI F47	SARFI-90	SARFI-80	SARFI-70	SEMI F47
1	175	219	175	189	876	873	876	541
2	232	232	232	232	459	459	459	218
3	241	241	78	87	255	255	313	117
4	78	78	244	50	118	118	119	62
5	12	12	12	244	22	23	24	16
6	261	261	261	261	11	12	13	5
7	246	239	77	239	5	10	12	3
8	239	240	234	77	3	8	8	1
9	240	137	239	234	1	6	6	0
10	77	246	246	246	0	0	0	0

The distribution of SEE incurred at each step of the iterative search is shown in Fig. 2 for the monitoring programme determined for sags specified by the SARFI-90 index. The gradual reduction in sag estimation error is apparent, as the error entailed by one monitor ranges from 409 to 1331 events and with five monitors the maximum error is 31 events. It can be seen that with the installation of eight monitors SEE is reduced to 2 sag events for 50% of the buses, to less than 5 events for 75% of the buses, and that error in the remaining 25% of the system buses is limited to 6 events.

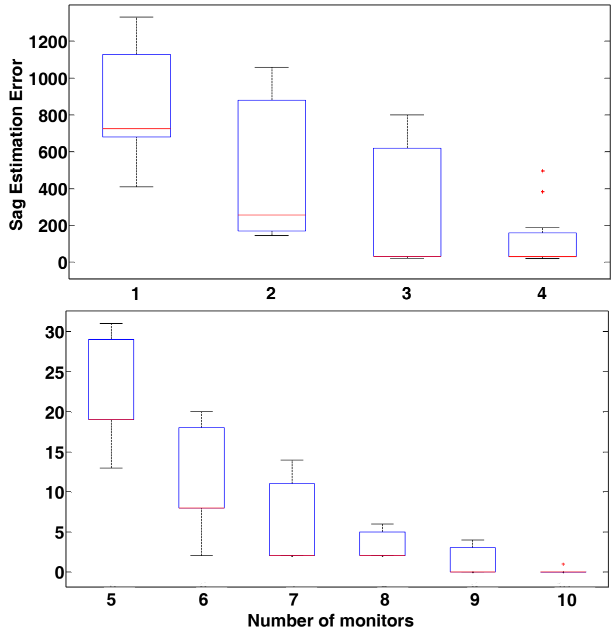

Fig. 2. Reduction of sag estimation error through the addition of monitors.

Comparison with optimal monitoring programme

The SMP obtained employing the SARFI-90 index has been compared with an OSMP determined using the method proposed in [2]. Using the same fault and system data, it was found that twelve monitors are required to register all voltage sags with a magnitude below 0.9 p.u. Five of these monitors are placed at 11-kV buses, two at 33-kV buses, and the remaining five at the secondary side of Yd transformers located at the end of 11-kV feeders.

System sag performance has been generated employing Monte Carlo simulations. Faults were simulated at random locations and with random properties and the characteristics of the sags caused by these faults were determined using fault calculation based on the Z-bus matrix. The random variables used in the simulations are: fault rate, fault location, fault resistance, fault type, and pre-fault voltages. The values for these variables are computed in each simulation based on their probability distribution function as in [5]. A total of 100 simulations were performed, each of them representing the system sag performance of an entire year.

The system sag performance corresponding to the 50th simulation was assessed employing both SMP and OSMP. A total of 17 faults were generated during that simulation, 9 line-to-ground LG, 4 line-to-line (LL), and 4 line-to-line-ground (LLG). The faults took place at the 11-kV and 33-kV networks. The location of the fault and the fault resistance values are listed in Table III.

Table III Fault data corresponding to the 50th simulation

kV	Fault location (p.u.)	Fault Resistance (Ω)	Fault type
33	0.946	1.594	LG
33	0.562	1.727	LG
33	0.916	1.279	LG
33	0.206	2.701	LL
11	0.789	13.281	LG
11	0.071	4.456	LG
11	0.252	2.663	LLG
11	0.980	9.029	LLG
11	0.959	23.081	LL
11	0.516	1.474	LG
11	0.614	14.751	LLG
11	0.763	3.656	LLG
11	0.542	8.496	LL
33	0.032	0.870	LG
33	0.342	1.374	LG
33	0.658	1.283	LG
33	0.264	1.629	LL

The estimation was performed with the OSMP consisting of twelve monitors and with the SMP developed with the proposed methodology using the SARFI-90 index, but utilizing only the first five selected monitors, in order to highlight the robustness of the fault location technique inherent in the proposed methodology. The comparison of the estimation of both monitoring programmes is illustrated in Fig. 3. It can be seen that there is a significant overestimation in the vast majority of buses by the OSMP, whereas the estimation by the developed SMP matches the real sag performance at most buses of the system. This can be explained by the fault location technique employed by each monitoring programme. The voltage drop fault location technique associated with the monitor placement method proposed in [2] is affected by changes in fault resistance and fault location, and the fault location technique implemented in the methodology proposed in this paper is immune to those two parameters.

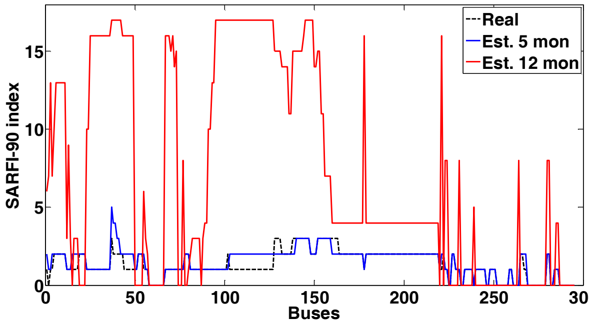

Fig. 3. System sag performance estimated by OSMP with 12 monitors and by SMP with 5 monitors.

The first fault listed in Table III wasp selected for detail analysis in order to clarify the underlying reason for the overestimation resulted from OSMP. The magnitudes of the voltage sags seen by all buses have been estimated with OSMP and SMP.

As shown in Fig. 4, there is a significant discrepancy between the real sag magnitude and the sag magnitude estimated by OSMP. While there is no voltage drop below 0.9 p.u. at any bus, the OSMP estimated voltage sags with magnitudes lower that 0.9 p.u. in more than 220 buses. This can be explained by the error incured by the voltage drop fault location technique in the selection of potential fault locations. The fault location algorithm of OSMP chooses fault locations based on the voltage drop registered at monitored buses but it is limited to a pre-defined set of fault locations and fault resistances values. Voltage sags caused by faults at locations and with fault resistance values other than the ones initially used cause the wrong selection of multiple fault location estimates and thus an erroneous sag estimation.

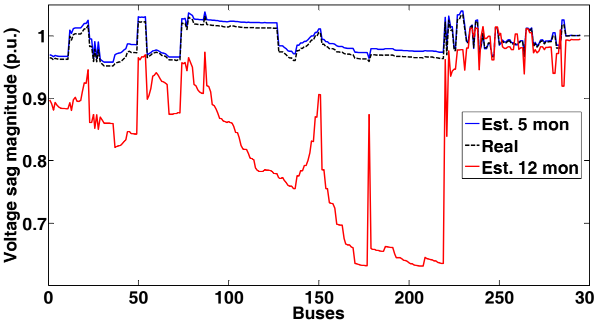

Fig. 4. System sag performance estimation for a LG fault.

The results of the 100 simulations performed, equivalent to 100 years of system operation, are similar to those obtained for the 50th simulation. The distribution of the SEE for both monitoring programmes is shown in Fig. 5. It shows that in 50% of the cases the sag estimation with SMP was 100% accurate, and in the remaining 50% of the cases the error was no greater than 2 sags. The estimation with OSMP on teh other hand, entailed an error of up to 3 sags in 50% of the cases, in 25% of the cases the error lied between 3 and 14 sags, and in the rest of the cases the error was greater than 14 sags reaching a maximum value of 32 sags.

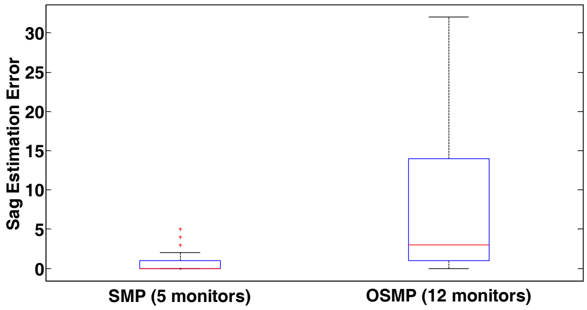

Fig. 5. Overall sag estimation error (SEE) for 100 simulations.

CONCLUSIONS

This paper presented a methodology that determines a range of monitoring programmes for estimating sag performance in the network using different sag characteristics and sag benchmarking methodologies. The proposed methodology offers the opportunity to utilities to choose a monitoring program specifically designed to estimate, not only general sag performance in the network but also number of sags with characteristics relevant to their customers, while balancing the accuracy and the cost of the monitoring programme. The methodology relies only on the bus-impedance of the network and voltage measurements at selected buses and, as it has been shown, is more robust than previously proposed approaches.

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