Integration of cost effective bus profiling in distribution networks

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Abstract: This paper presents initial results on the development of a methodology for cost effective monitoring and profiling of distribution network busbars with respect to different quality of supply phenomena. The initial results, presented in this paper, focus on monitoring for unbalance and voltage sags. Under the proposed monitoring framework, both voltage sags and unbalance can be monitored using the same set of monitors. The research builds on existing methods by combining probabilistic measures of the likelihood of a trip caused by unbalance or a voltage sag event to create a single unified probabilistic measure defined as the bus trip index (BTI). Utilizing the BTI, an optimal placement methodology is developed and tested by planning a set of monitoring locations in a 13 bus IEEE test network. The methodology is also applied to an operational case study to highlight the practical benefits of using the BTI in a real distribution network.

Keywords: voltage sags, unbalance, distribution system state estimation, voltage sag profile estimation monitoring.

1. INTRODUCTION

The current lack of monitoring in distribution networks keeps quality of supply phenomena (including, for example, voltage sags, harmonics, unbalance, flicker and transients) relatively hidden from distribution network operators (DNOs). Individual issues are usually tackled on a case by case basis by the DNO as and when they arise. Although DNOs would like to monitor for all power quality issues simultaneously, the level of monitoring that takes place is somewhat varied. For example, monitoring methods for voltage sags are much more advanced than similar approaches for unbalance.

Unbalance is created by single phase residential loads and/or network asymmetries and remains undetected due to a lack of three phase monitoring devices [1]. Voltage sags are caused by asymmetric and symmetric short circuit faults [2]. Both unbalance and voltage sags can seriously affect loads and generators by causing outages. Three phase power electronic devices and distributed generators are being installed in distribution networks in ever increasing numbers and both types of device are particularly sensitive to both unbalance and voltage sags. These types of loads also generate harmonics, and along with sags and unbalance, these three power quality issues are likely to be at the forefront of a DNO’s network reinforcement strategy.

The drive towards making power grids more flexible, observable and controllable (i.e. towards smart grids) is likely to result in a significant increase in the number of monitors distributed throughout the network. It is becoming increasingly important for DNOs to consider how they will intelligently process and interpret large amounts of information gathered by those monitors.

The first step on the path to a more intelligent distribution network will be to increase the amount of monitoring conducted throughout the network. These monitors will serve a variety of purposes, including feeding back into a distribution management system for voltage and demand control, advanced automation, fault detection, unbalance and harmonics monitoring, load profiling and optimal network reconfiguration.

Distribution system state estimation (DSSE [3-6]) is an emerging technique capable of processing information from a partially monitored distribution network. It uses both real time and estimated (pseudo) measurements to estimate the state of the system, and has been performed on both three phase and single phase models of power networks [3, 7]. DSSE typically uses the weighted least squares (WLS) technique in a similar manner to transmission system state estimation [8]. It has been shown that DSSE can be used to compute the expected distribution of the voltage unbalance factor (and hence monitor a network for unbalance) at any bus in the power network [7].

Estimating the sag performance of a distribution network is closely related to fault detection and can be accomplished using monitoring techniques known as voltage sag profile estimation (VSPE) [9, 10]. VSPE algorithms aim to reconstruct the voltage profile at all buses in the network during a voltage sag using a set of monitors much smaller than the number of buses in the network.

Traditional optimal monitor placement algorithms aim to select a number of locations in the network where monitors can be placed to accurately perform the task of VSPE [10] or DSSE [11, 12] independently. There are no techniques which are able to optimally monitor a network for both phenomena at the same time.
This paper proposes a road map towards development of comprehensive, cost effective methodology for monitoring and profiling buses in distribution networks. At this initial stage of development the focus is on simultaneous monitoring of voltage sags and unbalance in the network.

The central aim of the research presented in this paper is to develop a methodology capable of optimally selecting a set of monitors which are able to monitor the state of the network for both unbalance and voltages sags. The research builds on existing research to optimally select monitoring locations based on their ability to identify equipment trips caused by voltage sags in the power network. By focussing on equipment trips, the optimisation procedure is customer centric.

The work described in this paper combines two probabilistic measure for equipment trips caused by voltages sags and unbalance to create a single unifying probabilistic measure known as the bus trip index (BTI). The BTI approach is tested on a 13 bus IEEE test network [13].

2. PROBLEM DEFINITION

In most existing distribution networks the sag performance of the busbars and the level of unbalance are not continuously and comprehensively monitored. These phenomena remained unmonitored for two reasons: firstly, there is limited monitoring equipment installed in the network and secondly, there are few algorithms capable of processing raw data into meaningful information on unbalance and sags.

Two important research questions result from these observations:

1. Where do monitors need to be placed to maximise the visibility of sags and unbalance in the network?
2. What algorithms and methods are required to monitor the state of the network for unbalance and sags on a day to day operational basis?

2.1 Voltage Sags

The immunity of equipment to voltage sags is typically measured using the Information Technology Industry Council (ITIC) curve [14] or similar. Using the ITIC curve, it is possible to establish the duration and magnitude at which a device attached to a busbar will trip providing that it is compliant with manufacturing standards. The main limitation of the ITIC curve (and other similar voltage tolerance curves) is that it defines the operating region of equipment into two precisely defined regions. This is nearly never the case, and there will always be a region of uncertainty close to the edge of the curve where there will be a chance of an equipment trip [14].

2.2 Unbalance

The voltage unbalance factor (VUF) is defined as the ratio of the negative sequence voltage over the positive sequence voltage [15]. This is shown in equation (1).

\[
VUF = 100 \times \frac{\text{negative sequence voltage}}{\text{positive sequence voltage}} \tag{1}
\]

Unbalance affects many aspects of distribution systems. Derating of three phase machines is a particular problem which affects both DNOs and consumers.

DNOs are keen to reduce unbalance on Y-Δ transformers as the high levels of negative sequence currents generates a circulating current which causes overheating in the delta windings [16]. The operational limits of distribution networks are also reduced when unbalance is present; again caused by the introduction of negative sequence current [16].

From a consumer perspective, unbalance in distribution networks causes induction machines to operate at less than full torque as rotating negative sequence components reduce the total torque output. Unbalance also affects induction machines by causing mechanical damage, torsional oscillations and excessive heating which can only be overcome by derating the machine [17]. Synchronous generators and motors are also affected by excessive heating and increased mechanical stress. Even single phase loads are affected as the voltage supply tends to vary to a higher degree when unbalance is present.

High levels of unbalance ultimately result in equipment trips on three phase machines. Quantifying how much unbalance is required to cause a trip depends on the protection devices configured to protect a three phase machine.

At a network wide level, the UK grid code [18] and international standards [19] stipulate that unbalance in a distribution network should not exceed 2% for low voltage (LV) and medium voltage (MV) systems, and should not exceed 1% for high voltage (HV) (measured as 10 minute average values with an instantaneous maximum of 4%).

Unfortunately, despite the large number of standards detailing acceptable and unacceptable levels of unbalance within a distribution network, there are no equipment immunity curves available for unbalance.

2.3 Consumer Effects of Sags and Unbalance

DNOs and consumers are affected by voltage sags and unbalance in subtly different ways. DNOs are concerned with the economic effects of sags and unbalance in terms of failure to meet regulatory requirements, maintenance scheduling, contractual arrangements with important customers and increased losses. Consumers are interested in physical interruptions (trips) to their supply and associated economic losses. Therefore, the cost of sags and unbalance to consumers is not the same as the costs to DNOs.

If the effects of sags and unbalance on consumers are considered in an economic manner, the performance of the network can be measured by simply summing the number of sag and unbalance events multiplied by the resulting economic cost to the customer [20]. One way of considering the technical (rather than economic) performance of a network is to consider the probabilistic number of trips caused by unbalance or sags.

At this initial stage of research, the focus is only on the technical aspect of equipment trips from sags and unbalance. The methodology is focussed on the consumer rather than DNO, and therefore ignores the effects such as derating of...
transformers, overheating of transformers and general capacity reduction. Since it is only concerned with equipment trips, the methodology does not include the effects of unbalance such as heating of three phase machines, derating of machines and mechanical damage such as torsional oscillations.

3. BUS TRIP INDEX

It is generally not possible to definitively determine whether or not a device will trip during a voltage sag or a period of unbalance. Device trips depend on a number of factors including the duration of the event, the type of equipment attached to a busbar, the immunity curves for the equipment, the point on the wave at which the event hit (sags only), phase angle jump (sags only), current derating of attached machines (unbalance only) and local protection devices.

This research proposes that equipment trips caused by unbalance and equipment trips caused by sags are most straightforwardly considered as probabilities, namely, as a bus trip index (BTI). By considering the effects of unbalance and voltage sags as probabilistic measures, the two measures can be easily combined. The combined BTI can then be used to estimate the performance of the network for both phenomena.

3.1 Sag Trip Probability

The sag trip probability [21] is defined as the probability that equipment attached to a busbar will trip given a voltage sag. The sag trip probability aims to combine information on equipment type, sag duration and equipment immunity (ITIC curves) into a single probability. A high probability indicates that an equipment trip was likely. The sag trip probability can be straightforwardly expanded to a process trip probability [21] which is defined as the probability that an industrial process attached to a busbar will trip, given a sag.

The STP is defined mathematically as follows:

\[
\text{STP} = P(X > Y) = \int_0^\infty \int_0^x f_Y(y) dy f_X(x) dx
\]  

(2)

Where the sag duration is defined as a random variable \( X \) and the duration at which equipment will trip as a random variable \( Y \). \( f_X(x) \) and \( f_Y(y) \) define the probability density functions (PDFs) of both random variables \( X \) and \( Y \) respectively. Both \( X \) and \( Y \) are independent random variables.

\( f_Y(y) \) can be built by combining the probabilistic immunity curves [22] of equipment attached to a busbar. \( f_X(x) \) can be taken as a single value for a specific event, or the expected duration of sags within a given section of network. A probability density function \( f_X(x) \) for expected sag durations can either be built using general documented evidence (for example, from [23]) or by recording the historical sag durations and generating an expected probability distribution. The model for \( f_X(x) \) used in this research is taken from [23] and is represented as a lognormal distribution with parameters \( \mu = -2.4 \) and \( \sigma = 0.75 \).

3.1.1 Error in Sag Trip Probability Estimates

If the STP is estimated using an incomplete set of monitors, VSPE must be performed to estimate the during sag voltages throughout the whole network. VSPE can be accomplished using a variety of different algorithms including [9] and [24]. The details of the algorithmic methods are not repeated here for brevity. The VSPE algorithm used in this research is based on single measurement algorithms developed in [10, 24].

The STP at each busbar is calculated by estimating the during sag voltage at a busbar using VSPE. The accuracy of the STP estimate therefore depends on the accuracy of the VSPE algorithm.

Two of the most widely used VSPE algorithms [24, 25] are described and compared in [24].

The error in the during sag voltage estimate is dependent on the variation in voltages found from the results of short circuit studies at each of \( p_f \) possible fault locations. The error will also depend somewhat on the pre-fault voltage, and the fault impedance.

If [24] is used to perform VSPE, then the error of a during sag voltage estimate (at a specific busbar) can be assumed to entirely dependent on the set of (three phase vector) short circuit voltage estimates \( \{\hat{v}_1, \ldots, \hat{v}_p\} \), where \( p \) is the total number of voltage profile estimates. For both [24] and [9] the estimated voltage profile, \( \overline{\hat{v}} \), at the busbar is the average of these estimated short circuit fault voltages, as shown in (3).

\[
\overline{\hat{v}} = \frac{1}{p_f} \sum_{j=1}^{p_f} \hat{v}_j
\]

(3)

A more accurate estimate for the STP can be obtained without using an averaging procedure. To do this, the STP must be extended to incorporate voltage sag estimation algorithm accuracy into the STP result. Let \( V \) be defined as a random variable of the voltage (in per unit) measured at a busbar. Let \( W \) be defined the voltage at which the equipment will trip (as defined from the immunity curves). \( f_Y(y) \) is therefore a probability mass function with deltas at each \( \{\hat{v}_1, \ldots, \hat{v}_p\} \) as shown in (4).

\[
f_Y(y) = \sum_{j=1}^{p_f} \frac{\delta(\hat{v}_j)}{p_f}
\]

(4)

\( W \) is clearly not independent from \( X \), since the immunity curves describe these two items together. Let \( f_{W|X}(w|x) \) be defined as the joint probability distribution of both of these variables. By considering the immunity curve as a crisp boundary, an example \( F_{\text{STP}}(w|x) \) (cumulative probability mass function) is shown in (5).
The random variable \( V \) is entirely dependent on both the VSPE algorithm used and the set of monitoring locations within the network. Using this knowledge, a set of limits for the STP can be defined when the values for \( V \) are set deterministically. These limits are described in equations (7), (8) and (9).

\[
\begin{align*}
\text{Pr}(V_{\text{low}} \leq V \leq V_{\text{high}}) &= 1 - \alpha \\
\text{STP}_{\text{high}} &= \text{Pr}(X > Y \land V_{\text{high}} > W) \\
\text{STP}_{\text{low}} &= \text{Pr}(X > Y \land V_{\text{low}} > W)
\end{align*}
\]

In this research, a significance level of \( \alpha = 0.05 \) is used. The interval of \( \text{STP}_{\text{high}} - \text{STP}_{\text{low}} \) can be thought of as the interval where 95% of the time the true value of the STP will be found based on the variability of voltage sag depth caused by inaccuracies in the VSPE procedure. The smaller the difference between \( \text{STP}_{\text{high}} \) and \( \text{STP}_{\text{low}} \) the more accurate a given set of monitors is able to estimate the probabilistic number of trips in a network.

### 3.2 Unbalance Trip Probability

The probability of a trip directly caused by unbalance can be defined in a similar way to a sag trip probability. The lack of immunity curves for unbalance makes this a difficult task. Nevertheless, this research will propose that a model an unbalance trip probability can still be formulated. The model is general in nature, and can be easily integrated into more advanced models of unbalance equipment immunity as and when they become available.

A simple immunity curve for unbalance trips is proposed in Fig. 1. The curve shown in Fig. 1 includes the following assumptions:

- **Duration of the unbalance** is assumed not to affect the trip characteristics of end user devices and / or equipment.
- **Existing load and device derating (and therefore heating)** are assumed not to affect the trip characteristics of the device when exposed to varying levels of unbalance.
- **The device is assumed to trip as soon as the 2% statutory limit[19] for unbalance is reached.**
- **Unbalance is only assumed to affect devices connected to all three phases of the electrical network.**

\[
F_{XY}(w, x) = \begin{cases} 
0 & \text{otherwise,} \\
\frac{x > 20}{w > 0.95} \quad \frac{0.5 > w > 20 \times 10^{-3}}{x > 0.7} \quad \frac{0.5 > w > 10}{x > 0.8} 
\end{cases}
\]

Incorporating the uncertainty around the depth of the voltage sag, the STP is extended as shown in (6).

\[
\text{STP} = \text{Pr}(X > Y \land (V > W))
\]

Let \( P \) be defined as the voltage unbalance factor (VUF) where the equipment attached to a busbar will trip and \( f_P(p) \) define the probability density function of \( P \). In this study, the function \( f_P(p) \) is defined as a delta function centred at 2% as shown in (10). \( f_P(p) \) incorporates all the assumptions listed above. Because the model is general, it could be extended to incorporate more advanced models of device unbalance immunity.

\[
f_P(p) = \delta(2)
\]

Let \( Q \) be defined as the voltage unbalance factor at the busbar and the probability density function of \( Q \) as \( f_Q(q) \).

In a similar way to the STP, an interval \( UTP_{\text{low}} \) to \( UTP_{\text{high}} \) can be calculated by finding the \( 1 - \alpha \) interval on \( Q \), and then evaluating the UTP at each of these limits as shown in (13), (14) and (15).

\[
\text{Pr}(Q_{\text{low}} \leq q \leq Q_{\text{high}}) = 1 - \alpha
\]
\[ UTP_{low} = \Pr(Q_{low} > P) = F_Q(Q_{low}) \]  
\[ UTP_{high} = \Pr(Q_{high} > P) = F_Q(Q_{high}) \]  

3.3 Sag Caused Unbalance Trip Probability (SUTP)

Both STP and UTP are not independent, since an asymmetric sag can cause unbalance. The sag caused unbalance trip probability (SUTP) is the probability that equipment attached to a busbar will trip from unbalance, given a sag. It can be estimated from the set of voltage estimates \( \{\hat{v}_i, ..., \hat{v}_p\} \). For each estimate, the voltage unbalance factor can be computed (by evaluating the ratios of the negative to positive sequence voltages) to form a set of unbalance factor estimates \( \{VUF_1, ..., VUF_p\} \).

To calculate the SUTP, the random variable \( Q \) can be re-used with a new probability mass function \( f_q(q) \), as shown in (16).

\[ f_p(p) = \sum_{j=1}^{p} \frac{\delta(VUF_j)}{p_f} \]  
(16)

The SUTP can then be calculated using the same formula for the UTP in (11). Upper \( (SUTP_{high}) \) and lower \( (SUTP_{low}) \) limits for the SUTP can be defined in the same way as for UTP as shown in (13), (14) and (15).

3.4 Bus Trip Index

The bus trip index (BTI) is a probabilistic measure which represents the likelihood of an equipment trip during a pre-defined period of time, \( T \). The aim of the bus trip index (BTI) is to combine both the STP and the UTP into a single probabilistic measure (17).

\[ T \] is defined to be sufficiently short such that the change in load (and hence change in voltage unbalance) is almost negligible. \( T \) is defined as 30 minutes in this study. \( T \) can either be defined as a future time window or one that has just passed. If \( T \) is historical, it may contain a series of sag events. If \( T \) is futuristic, the number of sag events is a probability that depends on both network location, and fault type. Fault rates for a study can be determined from historical fault rate data held by the DNO using similar methodologies as those described in [26].

Let \( \{e_1, ..., e_N\} \in E(T) \) define the set of \( N \) observed or expected fault events in the network during a study period \( T \). The bus trip index for a study period is therefore defined as shown in (17).

\[ BTI(T) = 1 - (1 - STP(T)) \prod_{e_i \in E(T)} (1 - STP(e_i)) \prod_{e_i \in E(T)} (1 - SUTP(e_i)) \]  
(17)

The BTI can be used to calculate the probability of an equipment trip at a busbar caused by either unbalance or voltage sags by utilising information from a set of monitors in a distribution network. A case study of this is highlighted in the results section.

3.5 Objective Functions for Monitor Placement

An ideal objective function for a monitor placement study is to maximise the accuracy of both STP and UTP. This can be achieved by minimising the difference between \( STP_{high} \) and \( STP_{low} \) across all expected fault events and busbars, and minimising the difference between \( UTP_{high} \) and \( UTP_{low} \) across all time periods and busbars.

To achieve this goal, the performance of a monitor set is evaluated by considering the total number of potentially missed events (the total of missed trips and false alarms) during a series of fault studies and loading scenarios. The missed event (ME) metric for sags and unbalance is defined in equations (18) and (19). A monitor set is represented as a binary vector \( (m) \) with ones indicating that a monitor is installed at that busbar.

\[ ME_{STP}(m) = \sum_{i=1}^{K} \sum_{e \in e_T} 1 \forall STP_{high}(e,i) - STP_{low}(e,i) > 0.95 \]  
(18)

\[ ME_{UTP}(m) = \sum_{i=1}^{K} \sum_{e \in e_T} 1 \forall UTP_{high}(e,i) - UTP_{low}(e,i) > 0.95 \]  
(19)

Where \( e_N \) is the last in a set of proposed fault events, \( t_N \) is the \( N \)th (and last) of a set of 30 minute time periods. There are \( K \) busbars in the network. From the equations for missed events, an overall optimal monitor placement objective function (20) can be established.

\[ C(m) = \frac{ME_{UTP}}{K \times N_e} + \beta \frac{ME_{STP}}{K \times N_e} \]  
(20)

Subject to \( g_1(m) = m_1 + m_2 + ... + m_l + ... + m_N \)  
(21)

The coefficient \( \beta \) describes the relative weighting of STP to UTP. In this study, \( \beta \) is defined as the fault rate in the study time period.

The constraint \( g_1 \) limits the number of installed monitors. In this research, a monitor was always placed at bus 1, which makes \( m_1 \) equal to 1. The total number of installed monitors was limited to 3 by setting \( g_1(m) \) equal to 3.

Practical use of the objective function necessitates defining a time period (with associated loading) and a set of fault studies. A network must also be chosen. The set of time periods and loading periods could represent future loading scenarios, and potentially incorporate topology changes [21].

4. METHODOLOGY

The bus trip index concepts are introduced on the 13 node IEEE test feeder [13]. It was assumed that one monitor is already installed at the primary substation (as shown in Fig. 2).

The objective of the study is to exhaustively compute the best locations to place two additional monitors in the network to monitor sag trips and unbalance trips. Each monitor is able to measure the three phase real and reactive power injections and the three phase voltage magnitude at a busbar.
The IEEE 13 node test feeder was modified slightly by removing the transformer and replacing each of the cables and lines with balanced three phase circuits with a reactance of 0.02 per unit and a resistance of 0.004 per unit. This modification was carried out to ensure unbalance was generated only from variation in load, and not from an asymmetric unbalanced topology. The single line diagram for the network is shown in Fig. 2. The base loadings on the network were configured as 2.5 times the loading described in [13] and left unbalanced as defined in [13]. The VUF calculated over 24 hour period for bus 11 is shown in Fig. 3. Similar VUF variations are obtained for other buses in the network.

Fig. 2. The modified IEEE 13 node test feeder.

Each of the loads shown in Fig. 2 were modelled as residential loads unless they have been labelled with “Ind.”, where they are modelled as industrial. The study period was defined as 24 hours and based on residential and industrial load profile data given in [27]. Each time period $T$ was defined as 30 minutes.

The three phase fault rate for the network was assumed to be constant across all lines and cables at 0.348 [26] events per year. The coefficient $\beta$ was therefore $9.53 \times 10^{-4}$. The network was divided into 6 fault positions per line (using the method of fault positions [23]). Only three phase symmetrical fault events were studied in this research. The set of possible fault events therefore contains 72 events for each 30 minute interval giving a total of 3456 events.

To locate the best set of monitoring locations, 66 sets of monitors were tested over a typical 24 period. Each run was carried out with three monitors, and always with a monitor placed at bus 1. 66 runs were carried out as there are $12C^2 = 66$ different ways of placing two monitors at 12 busbars. It should be noted that exhaustively evaluating the performance of each monitor placement location in a large network in this manner will be computationally prohibitive. In this case, it is suggested that heuristic search techniques such as genetic algorithms could be used to place as described in [9].

Each real monitor was modelled with a standard deviation equal to 1% of the true value of the power or voltage. For all other busbars, pseudo-measurements were modelled with a 7% standard deviation [7].

For each set of monitors values for $ME_{UTP}$ and $ME_{STP}$ were calculated. The value of the objective function shown in (20) was then evaluated to find the best set of monitors.

In the study it was assumed that no sags caused unbalance trips and SUTP was zero. Since only three phase faults were simulated, the SUTP would be assumed to be zero.

5. RESULTS

5.1 Voltage Sags

Three phase faults were simulated throughout the whole network at 72 fault locations and for 48 different network loading profiles.

It was found that for all simulated three phase faults, any combination of three monitors will not miss any trips of equipment at all buses in the network. The calculated value of $ME_{STP}$ for any combination of monitors is always zero because a three phase sag anywhere in the network affects every bus in the network. It is almost certain that any three phase sag will cause equipment to trip at all buses in the network. Equipment may not trip, if the duration of the sag is short enough. However, since the expected duration of sag events is the same for all buses in the network, no missed sag events are registered.

5.2 Unbalance

The top 4 monitoring locations for unbalance in the network over 24 hour period are shown in Table 1.

Table 1. The performance of the top 4 monitoring locations for unbalance

<table>
<thead>
<tr>
<th>Monitors</th>
<th>$ME_{UTP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 7, 11</td>
<td>6</td>
</tr>
<tr>
<td>1, 10, 11</td>
<td>33</td>
</tr>
<tr>
<td>1, 11, 13</td>
<td>33</td>
</tr>
<tr>
<td>1, 4, 11</td>
<td>34</td>
</tr>
</tbody>
</table>

The best monitoring locations for unbalance are at buses 1, 7 & 11. These locations are probably selected for several reasons. Bus 1 and 7 are the busbars in the network with the greatest amount of power flowing in and out of the busbar. Bus 7 also connects to three separate busbars, therefore accurate knowledge of the voltage at bus 7 can help to predict the impact on unbalance at buses 8, 10, 13, 9 12 and 11.