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Sean Elphick

University of Wollongong, elpho@uow.edu.au

Sarath Perera

University of Wollongong, sarath@uow.edu.au

Neil Browne

Integral Energy

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Ripple Signal Amplification: Measurement, Modelling and Mitigation

Sean Elphick
Integral Energy Power Quality &
Reliability Centre
University of Wollongong,
Wollongong, NSW 2522
Email: sean@elec.uow.edu.au

Sarath Perera
Integral Energy Power Quality &
Reliability Centre
University of Wollongong,
Wollongong, NSW 2522
Email: sarath@elec.uow.edu.au

Neil Browne
Integral Energy
Huntingwood Drive,
Huntingwood, NSW 2148
Email:
Neil.Browne@integral.com.au

ABSTRACT

Use of high frequency ripple control signals for load control purposes has existed for many years. Although the level of the injected signal at the zone substation is generally small, amplification can occur when the network resonant frequency is close to the injected ripple signal frequency. Ripple signal level at the injection point is generally 5 – 7V in magnitude with reference to public low voltage systems. However, in some cases, network resonance can lead to voltage levels in excess of 10V that can lead to equipment problems the most prevalent being ‘racing clocks’. This phenomenon is essentially waveform distortion causing extra zero crossings. The paper presents the findings of a monitoring campaign and network modelling and simulation study carried out on a network owned and operated by Integral Energy. The potential mitigation strategies that could be used to alleviate ripple signal amplification are also discussed.

1. INTRODUCTION

Integral Energy (IE) uses ripple frequency signals to operate off peak tariff relays which control loads such as off peak hot water heaters and street lighting systems. One common frequency used by IE is 1043Hz which is close to the 21st harmonic of the fundamental frequency.

Ripple signal injection levels at Zone Substation (ZS) busbars are generally approximately 5 – 7V (L-N) when referred to the public low voltage systems. Tests have shown that signals levels above approximately 10V will begin to cause equipment problems [1]. High signal levels arise as a result of amplification of the injected signal due to the network behaviour at the injected frequency. Traditionally, amplification of injected ripple signals is most common in lightly loaded areas where the network consists of significant lengths of both overhead and underground cabling.

High signal levels can cause the ‘racing clock’ phenomena where timekeeping devices which rely on fundamental frequency zero crossings run fast due to the additional zero crossings caused by waveform distortion. Other effects of high ripple signals include flickering of dimmed lights or touch lamps and audible noise through speakers as well as devices with motors such as ceiling fans.

This paper details the findings of a monitoring campaign and network modelling and simulation study used to suggest potential mitigation strategies that could be used to alleviate ripple signal amplification.

Section 2 details the monitoring of signal levels on the feeder under study conducted during March 2006. Details of the development and implementation of the models used to analyse the feeder under consideration are provided in Section 3, as is an indication of the performance of the model with respect to field data. Section 4 presents the modelling results in relation to two well known mitigation strategies adopted to reduce the signal levels on the network to acceptable levels.

2 FIELD MONITORING METHODOLOGY AND RESULTS

Logging and analysis of the signal data is not straightforward. High data sampling rates are required to ensure that the signal is captured which leads to large volumes of logged data. This data then has to be analysed in such a way that only the signalling voltages are reported. There are currently no monitoring instruments designed to log ripple control signal frequencies over an extended period of time (e.g. one week). However, due to the fact that the frequency of the injected signal on the feeder under study is close to the 21st harmonic frequency, it is possible to monitor the 21st harmonic in order to get a reasonable idea of ripple signal levels. Further complexity is added to monitoring efforts due to the fact that the ripple signal is only present during injection periods. Injection periods generally last for approximately 3 minutes and may occur up to 20 times a day. Due to the pulsed nature of injection, over a 3 minute injection period, the ripple signal is generally ‘on’ or high for approximately 1 minute. Thus in order to gain a reasonably accurate idea of the ripple signal levels it is important to use sampling aggregation periods which are as small as possible however, this leads to large volume of data requiring analysis.

Fig. 1 shows the layout of the system under study. The lengths of the various sections of the feeder of interest and the type of construction are also indicated. Three monitoring locations (PS1-PS3) indicate the 11kV/400V padmount substations (PS) where the signal levels were monitored on the LV side. The monitoring point PS4, which is located about 100m

downstream of the zone substation (ZS), has been established to monitor the injected levels at the (ZS).

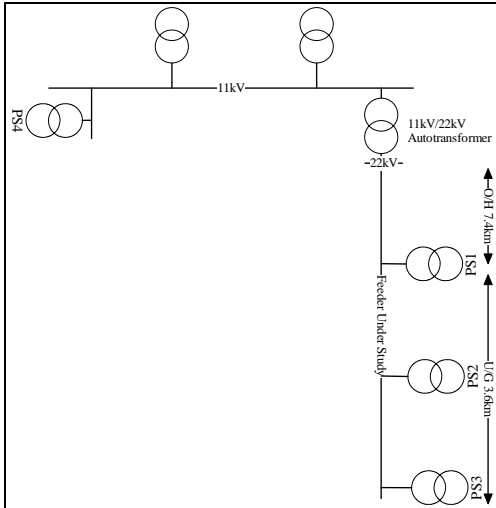


Figure 1: Layout of Monitoring Positions

Each site was monitored for one week. The instruments were configured to record voltage harmonics close to and including the 21st harmonic at 10 second intervals.

Due to the fact that the signal level is not persistent throughout the logging period it is not a straightforward exercise to analyse the data and calculate statistical parameters. It is possible to obtain an injection timetable, but this timetable is a guide only and injection may take place within ± 10 minutes of the stated time. This makes correlation of the injection timetable with the logged data very difficult. Thus some filtering of the data was necessary before an indication of the signalling levels could be determined. For this purpose arbitrary filtering was imposed on the data such that all 21st harmonic data values less than 1V (assumed background level) were discarded. Statistical parameters calculated on the remaining data were the average, 95th percentile and maximum values.

Table 1 gives the signal levels at each of the monitoring sites. It can be seen that the injected levels close to the ZS at PS4 of approximately 3 – 6V are not a cause for concern. However the remaining levels are of concern as there is evidence of amplification.

Table 1: Field Measurements

Site	Phase	Average (V)	95% (V)	Max (V)
PS1	A	6.56	10.87	12.13
	B	6.58	9.09	9.93
	C	6.41	10.43	11.64
PS2	A	9.02	13.89	16.56
	B	8.73	13.19	14.53
	C	9.35	14.08	15.65
PS3	A	8.41	13.00	15.03
	B	7.61	11.29	13.10
	C	7.99	11.95	13.32
PS4	A	3.36	5.25	5.82
	B	3.01	4.58	5.15
	C	2.89	4.28	4.80

3. NETWORK MODELLING USING PSCAD[®]/EMTDC[™]

Modelling of the feeder under study was undertaken using PSCAD[®]/EMTDC[™] using the modelling principles outlined in [1]. PSCAD[®]/EMTDC[™] allows the network to be modelled using passive elements. The model is constructed in such a way that only the ripple signal voltage is injected.

Figure 2 shows the detailed topology of the feeder under study. Overhead line sections are shown as thin lines and underground sections are shown as thick lines. Node numbers given are used to identify points along the feeder. The measurement sites as detailed in Section 2 are also shown on this diagram.

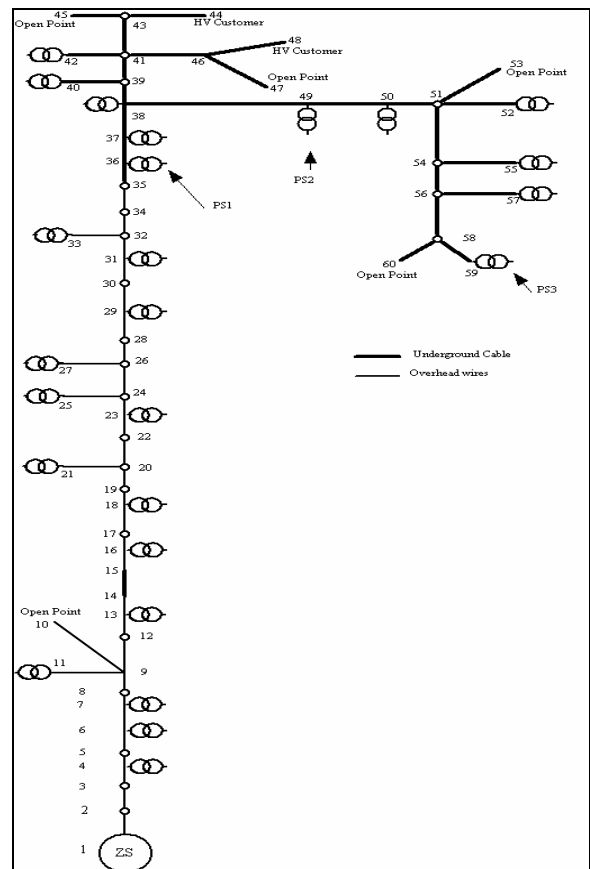


Figure 2: Detailed Topology of the Feeder under Study

3.1 MODELLING OF LOADS

Composite loads are modelled as parallel Resistive/Resistive-Inductive branches using the load models detailed in [1] as shown in Figure 3.

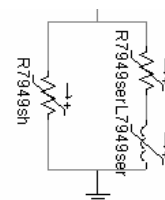


Figure 3: R-RL Load Model as detailed in [1]

With this model it is possible to represent any proportion of parallel connected purely resistive loads (R) and lagging power factor loads (series R-L). The

parameter used to vary the ratio of R to R-L load is defined as ‘xallocfraction’ and the parameter used to vary total load as the maximum load is defined as ‘Loadfraction’. The values of xallocfraction and Loadfraction values were varied to give a full range of loading conditions. For each simulation, xallocfractions of 0.3, 0.5, 0.7 and 1 (smaller value mean more R than R-L) were used and Loadfractions of 0.5, 0.7 and 1 (smaller values mean light load) were used. The HV customer loads indicated were also modelled using the above approach. For the HV customers, the xallocfraction and Loadfractions were fixed at 0.5 and 1 respectively. This means that the customers load is 50% R and 50% R-L and the customer always draws full load.

3.2 VALIDATION OF MODEL DATA WITH FIELD DATA

In order to test the validity of the model with field data several scenarios for xallocfraction and Loadfraction were applied to the LV customer loads. In the simulations, the ripple injection signal voltage is set at 100V making calculation of the signal amplification very simple. For the purposes of testing field data against simulation results, xallocfractions values 0.3, 0.5, 0.7 and 1 and Loadfraction values of 0.5, 0.7 and 1 were used.

Figures 4, 5 and 6 show a comparison of field measurement results and simulation results for PS1, PS2 and PS3, respectively. It should be noted that field measurements were done on all three phases whereas the simulation model assumes balanced behaviour across all phases. Phase-A measured field data is taken to be indicative.

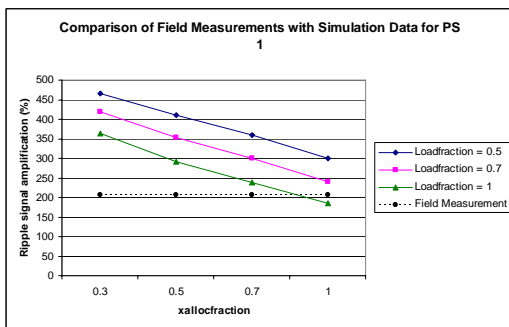


Figure 4: Comparison between Field data and simulation data for PS1

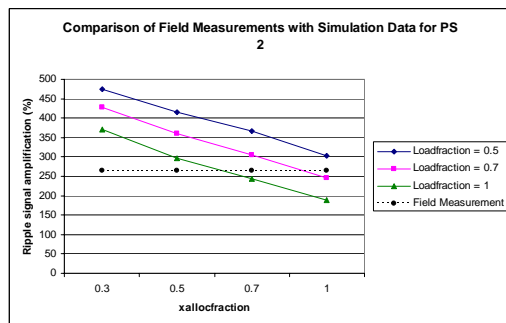


Figure 5: Comparison between Field data and simulation data for PS2

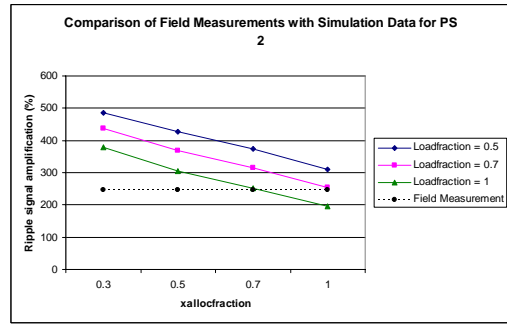


Figure 6: Comparison between Field data and simulation data for PS3

Figures 4, 5 and 6 indicate that the best correlation between the field measurements and the simulation results is achieved for Loadfractions values between 0.7 and 1 and for xallocfractions values between 0.7 and 1. This seems reasonable as the feeder under study is primarily residential (which will have a relatively large proportion of resistive loads).

3.3 INVESTIGATION OF NETWORK RESONANT FREQUENCY

In order to determine the resonant points of the circuit various frequencies were injected at the ZS bus-bar. This also allows determination of the level of amplification along the line. In all investigations, measurements were taken on the high voltage side of distribution substations at sites PS1, PS2 and PS3. Figure 7 shows voltage versus frequency curves for xallocfraction values of 0.7 and 1 and Loadfraction values of 0.7 and 1.

Figure 7 shows that the network resonant frequency is close to 1100Hz which explains why ripple signal amplification takes place on this feeder.

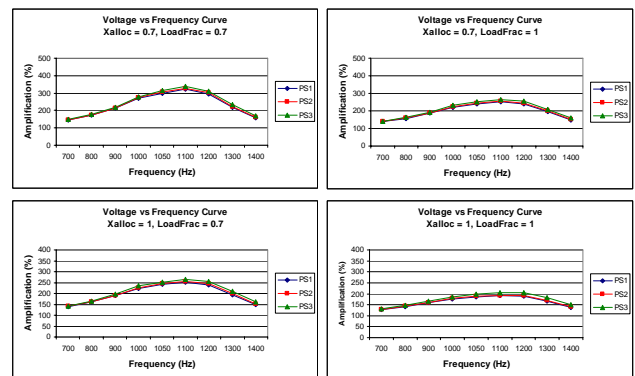


Figure 7: Voltage versus Frequency curves for various xallocfraction and Loadfraction values

4. RIPPLE SIGNAL AMPLIFICATION MITIGATION STRATEGIES

There are a number of mitigation strategies that may be used to resolve the problems caused by excessive ripple signal levels caused by amplification. These range from devices such as tuned filters installed in the consumer premises through to various network solutions. The purposes of the study is to examine

network wide solutions, thus small devices such as filters installed at customer premises will not be examined here.

Due to the fact that good correlation between field measurements and simulation measurements have been achieved the model outlined in Section 3 may be used to test mitigation strategies. The mitigation strategies investigated in this study are as follows:

- Increasing the total load on the feeder
- Connection of HV capacitors at 22kV
- Distribution transformer tuning

4.1 1050Hz VOLTAGE PROFILE

Before any mitigation strategies could be tested it was necessary to select some measurement points on the network in order to monitor the 1050Hz levels. This is necessary to ensure that mitigation strategies which control signal levels at the sites monitored in the field do not have adverse effects on other sites throughout the network. To this end 4 additional sites were chosen at approximately evenly distributed intervals along the feeder. Combined with the 3 field sites this gives 7 sites spaced out along the feeder. The measurement sites are at nodes 4, 18, 29, 36 (PS1), 42, 49 (PS2) and 59 (PS3) in Figure 2 and are on the secondary side the distribution transformers. Nodes 4, 18 and 29 are on the overhead section of the feeder and the remaining sites are on the underground section.

The signal voltage observed at each of the selected sites for xallocfraction values of 0.7 and 1 and Loadfractions of 0.7 and 1 is shown in Figure 8.

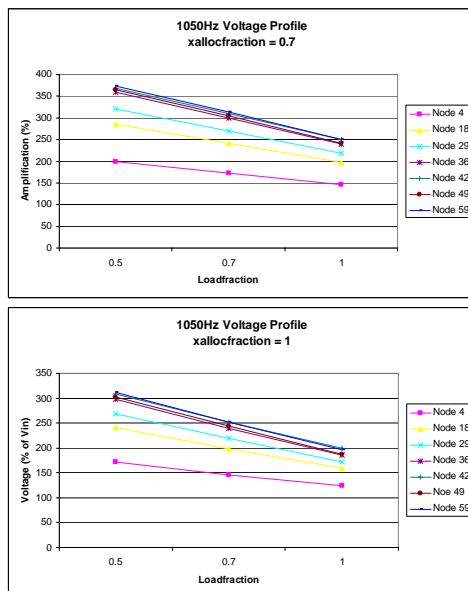


Figure 8: 1050Hz Voltage Profiles

4.2 INCREASE IN LOAD

Although not technically a mitigation strategy, an increase in the total load will have a significant impact on signal amplification levels due to damping. Traditionally, the areas most prone to ripple signal

amplification are lightly loaded developing areas and as these areas develop and more load is connected the problem tends to correct itself. Before any network augmentation is suggested it is prudent to examine the effect an increase in load will have on signal amplification levels. For this purpose the load was increased by a factor 2.

Figure 8 shows voltage versus frequency curves for a Loadfraction of 2 (double the load currently supplied) and xallocfraction values of 0.7 and 1. It can be seen that if the load were doubled, there would still be some amplification of the injected signal, however, the signal levels would be unlikely to cause equipment problems.

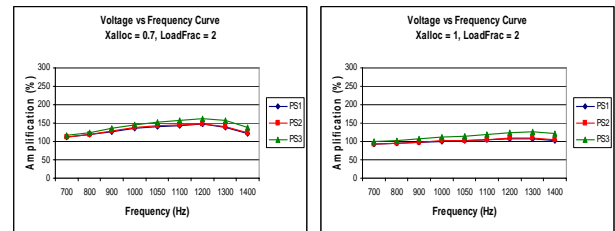


Figure 9: Voltage versus Frequency curves for double load

4.3 CONNECTION OF HV (22kV) CAPACITORS

This involves modification of the network so that the resonant frequency is moved away from the ripple signal injection frequency. This is achieved by adding either inductors or capacitors to the network. Previous studies [2] have shown that addition of inductance to the network is not a viable option therefore addition of capacitors was the only choice available.

There is no firm theory regarding the optimum point for placement of the capacitor banks on the network in relation to ripple signal level mitigation and thus trial and error is required. Three positions along the feeder have been examined:

- On the 22kV side of the 11kV/22kV autotransformer at the ZS
- At node 35 in Figure 2, approx. 7.4km from the ZS
- At the end of the feeder (node 58 in Figure 2), approx. 11km from the ZS

For each of these positions simulations were carried out to determine the capacitance required to reduce the signal amplification to 150% of the injected level at the end of the feeder (node 58). For capacitors connected at the ZS it has been found that a capacitance of 7.5 μ F or 1.1MVar is required for this purpose. If capacitors are installed at or near the overhead to underground transition point (node 35) a maximum of 1.6 μ F or 0.24MVar is required to reduce the signal level to 150% of the injected level at the end of the feeder. For capacitors connected at the end of the feeder (node 58) a maximum of 1.5 μ F or 0.22MVar is required to reduce the signal amplification to 150% of the injected level at the end of the feeder. Thus it can be concluded that less capacitance is required to control signal levels

if capacitors are connected downstream. This behaviour agrees with findings in [1]. Theoretically, addition of capacitance to the network should move the resonant point to the left or toward lower order harmonics. It is important to be careful to ensure that the new resonant frequency is not close to lower order dominant harmonic orders such as the 5th and 7th.

Previous studies [1, 2] have shown that addition of shunt capacitor banks to the network will be effective in reducing signal amplification and this is found to be the case here. Simulations show that addition of capacitance at the ZS will be effective in reducing the ripple signal amplification at the end of the feeder to an acceptable level. It can be seen that the resonant frequency is now somewhere between 800Hz and 900Hz and there will be significant amplification of harmonics near these frequencies particularly at light load. It should be noted that significant amplification (300% - 400%) occurs at approximately 500Hz or the 10th harmonic. Amplification of dominant low order harmonic orders such as the 5th and 7th may occur if this mitigation strategy is adopted, however amplification levels are not extreme and may be deemed acceptable depending on present and expected harmonic levels. Similar results were observed for the other two positions tested for capacitor bank placement.

Although this method is found to be effective in reducing signal levels at the end of the feeder to acceptable levels, a significant side effect is the attenuation of signal levels at sites close to the injection point. Although an uneven signal voltage profile is mentioned in [2] simulations carried out on the feeder under study show marked attenuation of signal levels at sites close to the injection point when shunt capacitors are installed at any of the test sites other than the ZS. Figure 10 shows the 1050Hz voltage profile for the test measurement sites listed in Section 4.1.

It can be seen that while addition of capacitors to the network at 22kV is effective at reducing signal amplification at the end of the feeder to an acceptable level, some sites close to the ZS will see marked attenuation of signal voltages down to levels unlikely to operate load control relays. This is especially true for capacitors placed at nodes 35 and 58. This attenuation of the signal levels renders this mitigation strategy unsuitable unless capacitors are installed at the ZS where the largest value of capacitance is required to reduce the signal magnitudes.

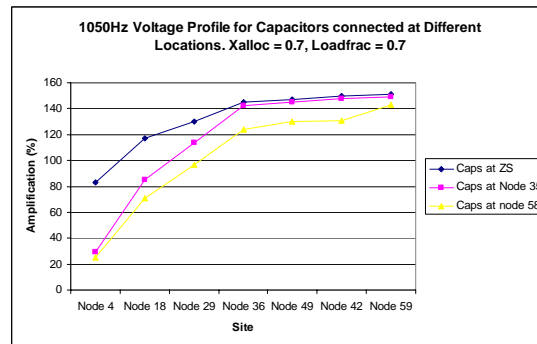


Figure 10: 1050Hz Voltages

4.4 DISTRIBUTION TRANSFORMER TUNING

This strategy involves connection of capacitors in parallel with the loads connected to selected distribution transforms distributed along the feeder. The capacitors are used to tune the transformer and load to create a partial series resonance near the signal frequency. This tuning effectively reduces the impedance of the transformer at 1050Hz meaning that the transformer/capacitor combination acts like a signal filter reducing the signal level. This mitigation strategy has a distinct advantage in that it uses low voltage equipment. In order to use the same size capacitors at every site the size of the distribution transformer and the load it supplies must be approximately equal. It is not possible to apply this technique at only one site due to the fact that the voltage rise across the transformer could create very high voltages which would be dangerous to equipment. There are 4 sites on the feeder under study which have similar loads and identical transformer sizes. These four sites are substations at nodes 59, 50, 55 and 57. Simulations determined that 50kVAr of capacitance connected in parallel with the load at each of these sites would be sufficient to reduce the signal to an acceptable level.

The effect of addition of 50kVAr of capacitance at each of the sites above on the network resonant frequency for a xallocfraction value of 0.7 is shown in Figure 11.

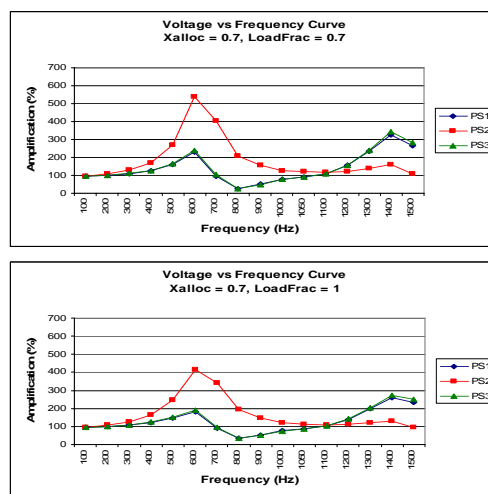


Figure 11: Voltage versus. Frequency Curves for tuning Capacitors

Figure 11 shows that the addition of the distributed capacitors has changed the resonance profile of the feeder considerably. Maximum voltage amplification now takes place at approximately 600Hz and there is a second resonance point at approximately 1400Hz. It can be seen that under all scenarios tested, 1050Hz voltage levels are at acceptable levels.

Once it was determined that the distributed capacitance was effective at reducing the 1050Hz voltage to acceptable levels at the field measurement sites it was necessary to check that the voltage profile along the feeder would be adequate to operate the load control relays under a range of loading scenarios. Figure 12 shows the 1050Hz voltage levels at the measurement sites outlined in Section 4.1 for a xallocfraction of 0.7 and Loadfractions of 0.7 and 1. Figure 12 shows that the 1050Hz voltage profile is acceptable at all sites along the feeder. At heavy load it can be seen that there is some attenuation of the signal at some sites, however, signal levels should still be adequate to operate relays. It can be seen that the signal level at node 49 is significantly higher than at any other site. This is due to the fact that this site is one at which capacitors have been positioned. The partial series resonance creates a rise in signal voltage across the transformer which is observed here.

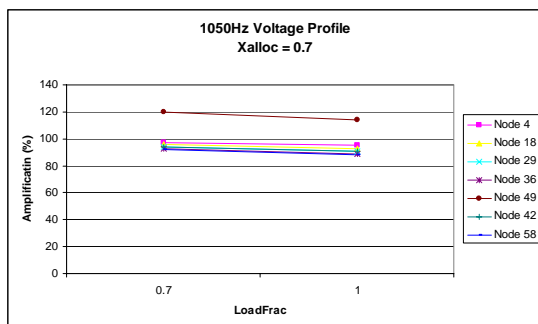


Figure 12: 1050Hz Voltage Profile

It is also necessary to investigate the effect of the addition of capacitors will have on the load at each of the sites where capacitors have been installed as the tuning of the distribution transformers will create a series resonance at a particular frequency. At this frequency large currents will flow and a large voltage rise will be seen across the distribution transformer. If the series resonant frequency is near a harmonic order significant damage to load equipment may occur. Theoretical calculations show that if 50kVAR of capacitance is connected to a 500kVA transformer with impedance of 4% on own base, series resonance will occur at approximately 790Hz. Figure 13 shows voltage versus frequency curves for the sites which have capacitors installed.

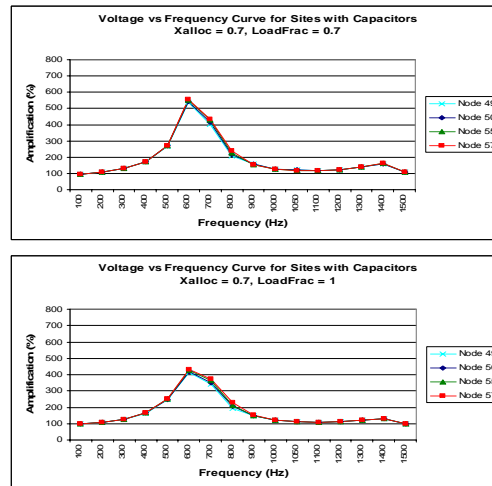


Figure 13: Voltage versus Frequency Curves for sites with Tuning Capacitors Installed

Figure 13 shows that addition of the distributed capacitance to the secondary side of the distribution transformer results in a series resonant point at approximately 600Hz with another at approximately 1400Hz. At this frequency the impedance of the distribution transformer/capacitor/load combination will be very small and any voltages of this frequency will induce large currents which will create a voltage rise across the distribution transformer. If harmonic voltages of this order are present high voltages would be expected on the secondary side of the distribution transformer. Under light load amplification of low order harmonics can be expected. This amplification of harmonic levels may be accepted as long as the voltage does not rise too high and the capacitors are rated appropriately.

5. CONCLUSIONS

This paper has detailed the findings of a monitoring campaign and network modelling and simulation study used to suggest potential mitigation strategies that could be used to alleviate ripple signal amplification. Simulations have shown good correlation between measured field data and the constructed network model.

Three ripple signal amplification mitigation strategies have been tested and the advantages and disadvantages of each examined. It has been found that the mitigation strategy involving distribution transformer tuning may be preferred as it presents a better signal voltage profile along the feeder and also uses 415V equipment.

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