The Reliability and Power Quality Performance of Overhead Lines – with reference to the Electrical Properties of Wood and Covered Conductors

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Abstract : In the information technology age, users of electricity services require both better reliability (fewer interruptions of supply) and better power quality (fewer disturbances, particularly voltage sags). The paper shows that the best way to reduce the frequency of interruptions and voltage sags is to reduce the number of faults on the distribution utility's low voltage and high voltage lines. Most utilities already use lines with wood poles and crossarms with the wood's electrical properties used to good effect. But a trend to "maintenance-free" designs will inevitably increase the frequency of faults, particularly those caused by direct and nearby lightning and by wind-effects. The most effective way to reduce the frequency of faults on existing overhead lines would be to develop an acceptable technology for cost-effective retro-fitting of insulating covers on those spans of existing lines near trees.

1. INTR0DUCTION

During recent years, electricity customers have come to expect a good quality of electricity supply. Earlier tolerance of interruptions has largely disappeared, a trend that has been exacerbated by the recent restructuring of the electricity supply industry. This (intolerance) is particularly so in urban areas where large-scale interruptions can cause serious societal dysfunction and in commerce and industry where interruptions can cause serious economic losses. The advent of an information age heavily dependent on digital electronics technology has brought with it recognition that power quality (PQ) has become an important technical-economic issue for both electricity suppliers and many of their customers. This is so for power quality disturbances that can cause mal-function of or damage to electrical and electronic systems and equipment – obviously, the vulnerability increases with "smartness" and sophistication of the systems and equipment and this even extends to some domestic appliances.

Historically, in Australia , there has been considerable use of hardwood poles and crossarms on overhead low voltage (LV), medium voltage (MV) distribution and high voltage (HV) sub-transmission lines. Most of the conductors are bare-metal, apart from some use of covered conductors (CC, either aerial bundled conductors, ABC or covered conductor thick, CCT) where lines pass through environmentally sensitive treed areas and more widespread use for MV lines in bushfire prone areas. As well having good mechanical strength and durability characteristics, the wood has electrical properties that can be utilized to minimize line faults. When dry, wood poles and crossarms provide effective "back-up" insulation for LV and MV voltages (at least to 22kV) in the event the air clearances are breached between bare conductors (by conducting objects such as tree branches) or the insulators fail. When dry and even when wet, utilisation of wood's impulse properties on LV, MV and HV lines can improve lightning performance markedly because the wood can add to the impulse insulation strength and because it possesses arc quenching capabilities [1]. However, a recent trend towards "maintenance-free" LV and MV lines using arm-less constructions and concrete or steel poles means that these desirable properties of wood will no longer be exploited to minimize fault rates on such lines.

This paper first identifies the sources of interruptions and power quality disturbances concentrating on those caused by line faults. This is followed by reviews of the technologies available to reduce fault frequencies and to minimize the consequential effects of interruptions and voltage sags. The important issues of bare conductors and "maintenance-free" lines are examined more closely, followed by a look at the possibilities for reducing the frequency of line faults and fault-induced voltage sags.

2. SOURCES of INTERRUPTIONS and PQ DISTURBANCES

2.1 Faults and Interruptions Faults on lines (and to a much smaller extent on line-connected equipment) are the cause of nearly all unplanned outages and these may be momentary or sustained. An interruption occurs if the supply to the customer(s) involves an outage on a radial line but is only momentary (less than a few seconds) if the fault-clearing breaker is reclosed successfully. The interruptions from sustained faults persist till damage has been repaired or switching has been carried out to provide an alternative supply. For appropriately designed lines, about 90% of lightning faults on lines are transient and allow successful reclosure, but this falls to about 30% for all other types of faults and these are sustained outages. Radial line faults cleared by fuses or isolated by sectionalisers always cause sustained interruptions. In contrast to LV reticulation and MV distribution lines, HV sub-transmission lines are mostly operated in parallel or as part of ring or meshed systems, so an outage on one line does not cause an interruption if appropriate protection and circuit breakers function correctly. Line faults also cause power quality voltage disturbances (sags and swells) with durations that equal the time it takes to clear the fault (< 1 second, usually 3 to 10 cycles if cleared by level 1 protection and a circuit breaker).

In Australia, well-designed transmission and sub-transmission lines operating at voltages ≥ 110 kV are usually shielded and lightning resistant, and so have low lightning outage rates (< 1 / 100 km-years) and total outage rates of about 1 / 100 km-yrs. Some 33 and 66kV lines are shielded and can also be lightning-resistant if they utilize wood to provide high insulation levels and if they have low footing resistances. However, most 33 and 66kV sub-transmission lines and nearly all LV and distribution lines (11 and 22kV) are unshielded and are vulnerable to lightning over-voltages. If appropriate use is made of the insulating and arc quenching properties of wood in crossarms and poles [1], such lines can have acceptable outage rates attributable to lightning. The word attributable was underlined because while the so-called lightning faults occur during thunderstorms, these are accompanied by high velocity winds of 50 to 100 km/hr, and it is difficult to distinguish lightning-caused faults from those caused by high wind effects such as contact from nearby trees, air-borne branches and clashing of conductors. There is strong evidence to suggest that about 80% of severe weather faults (thunderstorms or simply severe wind storms) are caused by wind effects. Severe weather fault rates usually account for about 70% of all faults.

The line outages that cause most interruptions are on radial unshielded overhead lines and those that cause most PQ voltage disturbances are on unshielded distribution and sub-transmission lines. Earlier data on average line outage rates (/ 100 km-yrs) for unshielded 33 and 66 kV wood pole/crossarm lines in Queensland for the years 1959 to 1973 given in [1, 2] are -- total forced outage rates of 7.6 and 5.7, lightning outage rates of 5.2 and 2.9, and sustained lightning outage rates of 0.4 and 0.4 / 100 km-yrs respectively (in providing these, the authors' figures for lightning outage rates would really be those associated with both thunderstorm lightning and wind). The same source gives outage rates for 11 kV lines in south-east Queensland – total 11.5, severe weather 8 / 100 km-yrs; of the last, only 8% of the faults attributed to lightning were sustained, whereas 61% were sustained for other weather-induced (i.e. not lightning) faults. There is a natural dispersion of almost 2 to 1 in the annual outage rates around the average rates, e.g. for the system of 33 kV lines in south-east Queensland over the period 1967 to 1972, the lightning outages varied between 5.9 and 11.7 / 100 km-yrs. It is of interest to make comparisons with current (2002) data for overhead 33 and 11 kV lines in south-east Queensland [3] (and bearing in mind the dispersion just referred to) – 33kV, total 14.6 / 100 km-yrs of which 6.3 were permanent; - 11 kV, total 20.3, of which 8.4 were permanent. It is revealing to separate urban and rural 11 kV feeders, the former are selected as having a load density > 300 kVA/km (in some cases, this distinction does not apply over a whole feeder). The line fault rates are – urban, 43.8 (permanent 18.1) and rural 14.6 (permanent 6.1) / 100 km-yrs. It seems most likely that the predominant cause of the difference between urban and rural outage rates is the presence of trees near many of the urban 11 kV feeders.

2.2 Power Quality Disturbances

There are three main classes of power quality disturbances – voltage disturbances (sags and swells), waveform distortion (steady-state deviation from an ideal sinusoidal waveshape) and transients (oscillatory and impulsive) [10,11]. . The most important one is voltage sag and this is discussed in this section. Voltage sag is a decrease in rms power frequency voltage to between 0.1 and 0.9 pu for durations from 0.5 cycles to 1 minute. Voltage sags are caused by following - .short circuit faults in the distribution and transmission network, temporary overloads, starting of large motors, certain switching operations, faulty intermittent electrical connections (going open circuit), and faulty tap changers.

Short circuit faults can cause voltage amplitude drops to 20% of the pre-fault voltage with durations determined by the time taken to clear the fault, usually about two to eight cycles. Voltage sags due to induction motor starting last longer, with typical durations of seconds to tens of seconds. For single and double line–to-ground faults, the voltage sag(s) appear(s) on the faulted phase(s) at nearby locations on the network. Usually, there will be an accompanying voltage rise (swell) on the healthy phase(s); on a solidly grounded system, this will not be large and is always less than 1.4 pu; for a resistance grounded system, the rise will be larger and may approach 1.73 pu. The longer duration and deeper voltage sags will usually cause power electronics loads to trip or mal-function.

The current interest in voltage sags is mainly due to the problems they cause to adjustable speed drives, process control equipment and computers. Some types of equipment trip when the rms voltage drops below 90% for longer than one or two cycles. If this occurs on the control equipment of large industrial processes, eg a manufacturing assembly line or a paper mill, the resulting damage attributable to the voltage sag can be very expensive. The effect of voltage sag on equipment depends on magnitude and its duration. According to Arrilaga [12], 40% of the sags monitored are severe enough to exceed the tolerance standard adopted by computer manufacturers. The voltage sag performance of the Energex network in Queensland for 1999/2000 financial year is shown in Figure 1 [13].

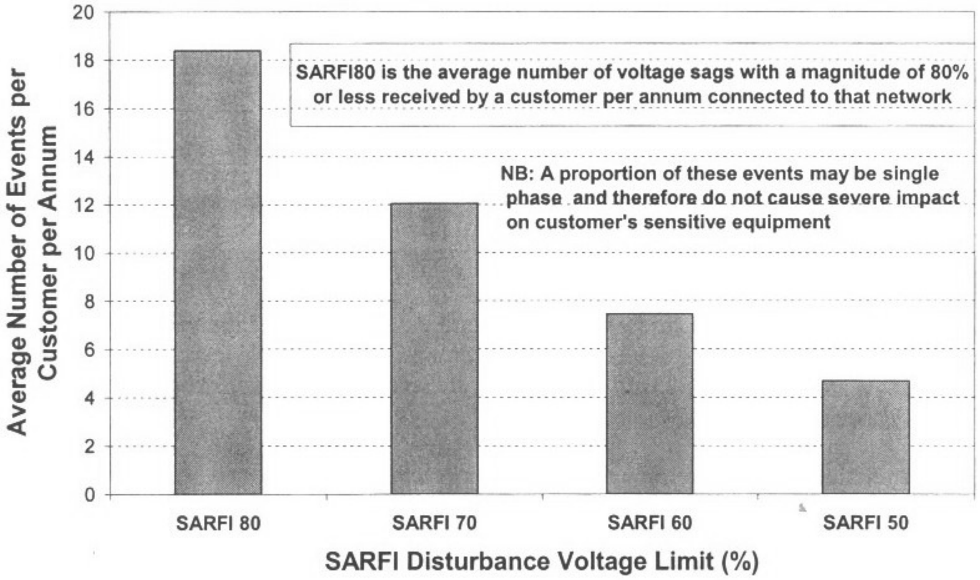

Figure 1 - Average number of voltage sags with different levels of magnitude per customer per annum for total Energex area –July 1999 to June2000 [13].

2.3 Technologies to Reduce Line Faults In broad terms, there are three approaches to improving reliability and reducing the impact of voltage sag PQ disturbances – (1) deal with the cause by reducing the frequency of faults, (2) deal with the effects of the faults on the power system (a) by ensuring that most of the faults only cause momentary outages, (b) reconfiguring radial lines into ring or meshed networks and the installation of more in-line sectionalisers and reclosers (particularly "intelligent" reclosers) thus preventing or minimizing the extent of interruptions, and (3) dealing with the fault-caused effects of voltage disturbances on the performance of the customers' equipment by improving its resistibility to such disturbances. The first two are the responsibility of the power system company and will be considered here; the third is for the manufacturer and the customer to deal with, see the next paragraph. The technologies for reducing the frequency of line faults are well known. They include – for shielded lines, increase insulation levels and / or reduce footing resistances; **-** for unshielded lines; the optimum use of wood's insulating and arc quenching properties, install more line surge arresters, increase air clearance between conductors to avoid clashing, improving line maintenance strategies, more tree clearing and trimming, use of covered conductors (ABC or CCT); and greater use of underground cables.

Voltage sags for critical loads (e.g. electronic controllers or computers) can normally be avoided by using commonly available uninterruptible power supply systems. To prevent the sag problem for the whole plant, high energy storage devices have been recommended with fast transfer switches that can switch to an alternate feeder within a few milliseconds. Ferroresonant transformers (also known as constant-voltage transformers) can usually handle most voltage sag conditions. CVT's are attractive for constant low-power loads, and they should normally be sized about four times greater than the load. Other techniques are available, such as the use of magnetic synthesizers for larger loads (several kA) [10].

2.4 "Maintenance-Free" Lines Wood shrinks with seasoning and deteriorates with age because of weathering (mainly on top surfaces of crossarms) and fungal decay and termite attack (mainly on poles in ground). So lines constructed with wood poles and crossarms require maintenance – for crossarms, during the initial period of seasoning and after ageing; poles, even those treated with preservatives, regularly throughout their service life. The development of "maintenance-free" designs for LV and MV lines usually involves firstly the use of armless constructions and then the use of concrete or steel poles. So, wood crossarms are first eliminated and then conducting poles replace wood poles. This trend usually results in more compact line designs with lower insulation levels and smaller conductor spacings.

It is obvious that the removal of wood in line designs means that no use can be made of its insulating and arc quenching properties. So wood-free designs for LV and MV voltage lines have no "back-up" insulation at **50 Hz** . **Lightning** over-voltages can cause flashovers of phase-ground insulation, phase-phase insulation or both. Over-voltages **induced** by nearby lightning flashes to ground stress phase-ground insulation only, and rarely exceed 250 kV in magnitude and a few µs in duration. So lines with a 1.2/50 µs impulse insulation strength of over 200 kV are immune to induced over-voltages; this includes lines of 33 kV and above and LV, 11 and 22 kV lines with insulators in series with at least 0.5 m of wood in the phase-ground path. This means that even the last set of lines that use armless constructions mounted on wood poles are also immune except when earthed stay-wires are fitted at the pole top (a small length of wood or fibre-glass in the phase-stay wire-ground path can overcome this). However, LV and 11 kV lines using armless constructions mounted on conducting poles are vulnerable to flashovers from induced lightning over-voltages because their insulator strengths are only about 40 and 125 kV. For the common conductor height of about 10 m, field data and theoretical calculations show that 40% of induced over-voltages exceed 40 kV and 10% exceed 125 kV, and so cause flashovers and faults. Induced over-voltages are much more frequent that direct strike over-voltages, so LV lines with armless constructions on conducting poles are very vulnerable to induced lightning flashovers and even 11 kV lines will experience such flashovers. The solutions include the use of line arresters (on all phase conductors and on at least every 6th pole), or for 11 kV lines increasing the insulation to at least 175 kV (11 kV insulator plus a short length of fibre-glass or a 22 kV insulator). Different considerations apply to over-voltages caused by **direct lightning** strikes to un-shielded lines. Here all strikes cause a flashover to ground, regardless of insulation level, with a probability $p_1 \approx 1$, and the same strike will then produce quasi-backflash voltages that often also cause flashover of phase-phase insulation. So the lightning outage performance of un-shielded lines is mainly controlled by the probability p_2 that flashovers lead to power fault currents and outages. For well-designed lines with optimal use of the arc quenching properties of wood poles and crossarms, p_2 can be in the range 0.2 to 0.4 [1] and hence unshielded lines can have acceptable direct strike outage rates, e.g. 2 to 10 / 100 km-yrs. But for armless constructions on conducting poles, there is no wood to provide an arc quenching capability and so direct strike outage rates must increase , by a factor of $1/p_2$. There must be a similar increase for armless constructions on wood poles, because here direct strikes will always cause phase-phase flashovers and hence faults because there is no wood in the phase to phase path(s). The overall consequence of the total and even partial elimination of wood on "maintenance-free" lines is a significant increase in the frequency of line faults. The only available technical solution is more use of line arresters on every phase conductor and at least on every 6th pole. This may cause another reliability problem, because distribution class surge arresters can fail for a variety of reasons [4] and cause line faults unless the arresters are fitted with explosive earth-lead disconnectors.

2.5 Covered Conductors Many faults that occur on lines with bare conductors during thunderstorms and wind storms are caused by the presence of nearby trees and to a lesser extent by conductor clashing. The tree problem is the result of close-by and overhanging branches, as is often the case for LV and distribution lines in the "leafy" suburbs of urban areas. The obvious solution of expanding tree clearing and trimming programs is often not acceptable because trees are aesthetically pleasing in such suburbs and most people will not tolerate their removal or severe (and therefore unsightly) trimming. Underground cables are prohibitively expensive and so the alternative of using covered conductor technologies (ABC or CCT) is an attractive proposition to reduce fault rates on LV, 11, 22 and 33 kV lines. The experience in a number of overseas countries, notably in Japan, Korea, and in Scandinavia, is that the fault rates of CC lines can be as low as 1/10th of those for comparable bare conductor lines. CC is also used to improve safety against accidental contact with "live" conductors either associated with trees or in wire-down situations. In Japan and Korea, CC is mandatory in urban areas, and in America, CC conductors are used where lines pass through trees. For new lines, the CC technology is proven and affordable, because the additional cost of using CC is only about 25% above that of using bare conductors. However, the cost of replacing existing bare conductors with CC is much higher (but far less than replacement with underground cables). Very recently, a new technology has become available for retro-fitting insulating covers on existing bare conductors of LV and MV lines [e.g. 5]. It is being trialled in Australia and some overseas countries, and while the application seems promising, the currently available line covers are too heavy (causing sag problems on spans in excess of about 50 m) and are too bulky (causing unacceptably large wind forces during thunderstorms and wind-storms or heavy ice loads during snow storms).

3. DISCUSSION and SUGGESTIONS for the FUTURE

As described above, line faults cause momentary and sustained line outages, and these can result in momentary or sustained interruptions, the former of duration less than 1 minute, while the latter can have durations of many minutes and even hours. It is relevant to give quantitative data to demonstrate how the average line outage rate data given in Sect 2.1 "translate" into average customer interruption times (SAIDI) and interruption frequencies (SAIFI); for distribution companies (DistCos), these exclude interruptions from generation/transmission events. Queensland data are first presented [6, 7], then data from NSW and Victoria [8], and these are then compared with data from some overseas countries [9].

Energex supplies 1.1 million customers in 25,000 km^2 of urban and rural areas of south-east Queensland using about 38,000 km and 12,000 km of overhead lines and underground cables. There are 1,780 km of overhead 33 kV lines and the lengths of urban and rural overhead 11 kV lines are 3,266 and 13,264 km. The 2001/2002 SAIDI figures (mins/yr) are – urban 145, rural 235 mins (total 175), and the SAIFI figures (interruptions/yr) are – urban 1.54, rural 2.31. The dispersion of the average total interruption times/yr is 220 to 90 around the average of 156mins over the last 10 years. **Ergon Energy** supplies 570,000 customers in 1.7 million km^2 of urban, rural and remote rural areas of Queensland using 140, 000 km of lines including 65,000 km of SWER lines. Its 2001/2002 SAIDI figures are – urban 179, rural 517, remote rural 997 mins (total 437), and the corresponding SAIFI figures are –2.3, 4.9, 5.6 interruptions (total 4.2). Ergon's urban indices are not very different from those for Energex, but there are large differences between their rural indices, as is to be expected because Ergon supplies vast rural areas. The **NSW** indices are for two largely urban DistCos and four largely rural ones – over the last 6 years, the urban SAIDIs vary between 70 and 100 mins and the rural ones between 110 and 250 mins, with corresponding SAIFIs of 0.65 to 1.25 and 1.2 to 2.85 /yr. The **Victorian** indices are also for two largely urban and four largely rural DistCos – urban SAIDIs from 40 to 130 mins and rural ones from 60 to 270 mins, with corresponding SAIFIs from 0.4 to 1.7 /yr. Summarising for the three States, the urban SAIDIs range from about 40 to 150 mins/yr while the rural ones range up to about 500 mins/yr (excluding remote rural); the urban SAIFIs are from about 0.4 to 1.7 /yr while the rural ones are up to about 5 /yr. A somewhat cursory search (in literature and web-sites) of **overseas** data on average yearly interruption times for several countries gave the following **-** < 10 mins in Japan (< 5 in Greater Tokyo), < 20 mins in South Korea, < 40 mins in most of America (interruptions from extreme natural events are usually excluded). The reasons for the relatively poor Australian indices of reliability are considered next and the "lessons" that can be inferred from the overseas indices are used to make suggestions for the future.

The Energex system is used as the illustrative example. Firstly, the reasonable presumptions are made that nearly all of the interruptions are caused by line outages and that most are due to outages on radial lines. An illustrative **urban** 33/11 kV zone substation in Brisbane is supplied by 2 underground 33 kV cables arranged in a ring so that a single fault will not cause an interruption. There are 7 outgoing overhead 11 kV radial feeders of lengths 3.6 to 13.4 km (total 46.2 km) each controlled by a reclosing circuit-breaker. So an 11 kV line fault causes either a momentary interruption or if permanent a sustained interruption that persists till the fault is isolated by in-line switches and supply is restored by closing a tie to a neighbouring feeder through a normally open switch or the fault is repaired. The average total outage rate in 2002 for an urban 11 kV feeder is 43.8 / 100 km-yrs of which 18.1 are sustained (Sect. 2.1) and so the average number of faults in the year on any one feeder is 1 to 6 and the number of sustained interruptions is 0 to 3; the average number of sustained interruptions is 1.2, which makes up most of the urban SAIFI of 1.54. The total number of faults on the 7 feeders in the year is 20. This value is not very different from the average number 18 / yr of voltage sags of magnitude ≤ 80% (Sect. 2.2) experienced by a customer connected to that urban 11 kV network, suggesting a reasonable link between numbers of total faults and voltage sags, even though the dispersion of both fault and sag rates is at least 2 to 1. An illustrative **rural** 33/11 kV zone substation in a farming area south-west of Brisbane is supplied by 2 overhead 33 kV feeders operated in parallel, so that again a single fault will not cause an interruption. There are 5 outgoing overhead 11 kV feeders of lengths 40 to 197 km (total 550 km), each controlled by a reclosing circuit breaker; there are also in-line reclosers in two of the feeders and drop-out fuses on some of the longer spurs. So the consequences of an 11 kV fault are similar to those for the urban 11 kV feeder, although there is about a 10 to 1 difference in line lengths. The average total outage rate in 2002 for a rural feeder is 14.6 / 100 km-yrs of which 6.1 are sustained (Sect 2.1) and so the average number of faults in the year on any one feeder is 6 to 29 and the number of sustained interruptions is 2 to 12. The average number of sustained interruptions is 6.7 ignoring the presence of in-line reclosers and dropout fuses on spurs; this is much larger than the Energex rural SAIFI of 2.31 but is closer to the Ergon rural SAIFI of 4.9. The average interruption times for the illustrative urban and rural examples cannot be estimated from the outage rate data because they are dependent on the presence of in-line reclosers, fuses on spurs, the capacity to isolate faults and the availability of alternative sources of supply, as well as the times needed to repair faults. Perhaps it is sufficient to say that it is not surprising that the urban SAIDIs for both Energex and Ergon are about 150 mins/yr and their rural SAIDIs are over 200 and over 400 mins/yr.

It is now of value to speculate on the reasons for the poor average interruption times experienced by customers in Australia compared to those for the named overseas countries (Japan, Korea, and America). The environmental impacts (such as severe weather) are not very different. The proportion of underground cables is also not very different. But, the demography of Australia is such that population (and customer) densities are much smaller than those in Japan, Korea and many parts of America. Clearly then, the DistCos in the latter group have the revenue base to achieve more robust distribution networks – more parallel, ring or meshed networks of distribution feeders with appropriate protection and circuit breakers, more in-line reclosers and sectionalisers, etc. So even if the line outage rates are as high as those in Australia, the frequency and duration of interruptions to supply will be much smaller in the overseas distribution areas. However, if the frequency of faults remains high, so will the frequency of voltage sags experienced by customers (despite the lower interruptions). But it seems that there must be another major reason why the overseas interruptions are smaller, particularly in Japan and Korea. This reason has already been referred to in Sect. 2.5 – the greatly reduced fault rates that stem from the widespread use of covered conductors on LV and MV lines, and which is mandatory in Japanese and Korean urban areas. The reduced numbers of faults reduce both interruption times and the frequency of voltage sags.

The final matter is the application of the fore-going to consideration of suggestions for the future quality of supply to Australian customers. The Energex urban and rural examples will again be used for illustrative purposes. It is obvious that the problems of frequency and time of interruptions and of PQ voltage sag frequencies on the **urban** example with relatively short 11 kV feeders are due to the frequency of faults and to the fact that the feeders are radial. Because the service area is relatively small, there are convenient tie-points between neighbouring feeders, but currently these are normally open. Wherever possible, these should be closed with the network of feeders then operating in a ring or mesh with the addition of in-line reclosers and appropriate protection on them and on the zone substation breakers. These measures would greatly reduce the interruption times but not the voltage sag frequencies. The last is a matter of concern because the service area contains a significant number of commercial businesses, a major shopping centre, shops, a large hospital as well many residences. Because of the shielding provided by trees and buildings, lightning is not a significant cause of faults and so the high 11 kV line outage rate (of 43.8 / 100 km-yrs) is due to other causes, such as fauna, vehicular impacts, wind–induced conductor collisions and wind-induced contact with tree branches. As already stated in Sect.2.1 and 2.5, it is very likely that the presence of trees near the feeders is the dominant cause of the faults. The option of extensive trimming of branches and clearing of trees is not available because of the pleasing aesthetic appearance of the “leafy” suburbs in the service area.. So the most practical option is the greater use of covered conductors on the overhead lines and on the poles fitted with earthed-frame equipment (mainly distribution transformers). As discussed in Sect 2.5, replacement of overhead lines by underground cables and bare conductors by ABC or CCT is too expensive, and so the most practical solution is to retro-fit insulating covers on the existing conductors on vulnerable poles and spans. The technological challenges are to have available line covers that are not bulky and heavy, and that can be installed with live-line techniques at acceptable cost. It may be that the best solution for this urban example would be an appropriate combination of both ameliorative measures (making the 11 kV network of feeders more robust and the selective retro-fitting of covered conductors). The cause(s) of the quality of supply problem(s) for the **rural** example are quite different. Although the line outage rates are not small (14.6 / 100 km-yrs), the dominant problem is the long lengths of the radial 11 kV feeders (average 110 km, one 197 km) and their exposure to all kinds of faults particularly lightning strikes. The service area contains a wealthy farming community with extensive use of irrigation and a local town of about 2500 people. The interruption problem could be eased by installing more in-line reclosers and sectionalisers and by the more extensive use of line arresters. But the dominant cause of the problem(s) is that the 33/11 kV zone substation (which was built over 50 years ago) is no longer near the centre of the area it services and so long radial 11 kV feeders are required to supply the most distant customers (up to 80 km from the substation). Serious consideration should be given to another 33/11 kV zone substation located so as to reduce the maximum lengths of the re-arranged feeders to less than 100 km. Because of the wealth of the area and the increasing sophistication of the electrical equipment and appliances used by its customers, the installation of the new substation is probably overdue. All of the quality of supply problems for both the urban and rural examples will be exacerbated if increasing use is made "maintenance-free" lines (Energex makes some use of armless constructions on 11 kV lines, but at this stage, only occasionally). As discussed in Sect. 2..4, the presence of "maintenance-free" will increase the frequency of faults, but this increase can be countered by installing more line arresters.

4. Conclusions

It has been demonstrated that faults on unshielded radial overhead lines are the cause of the relatively high interruption frequencies and times to Australian customers compared to those in overseas countries such as Japan, Korea and America. The faults on all lines also cause momentary interruptions and PQ voltage disturbances particularly voltage sags. The occurrence of interruptions can be reduced by making the distribution network of feeders more robust, by using measures which introduce redundancy (particularly in urban areas) and which reduce the extent and duration of line outages. In urban areas with aesthetically pleasing "leafy" suburbs, the frequency of faults due to contact with tree branches should be reduced by retro-fitting insulating line covers onto the conductors on selected spans and poles. In rural areas, feeder lengths should be limited to less than 100 km and increasing use should be made of line arresters.

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