Optimal network topology and reliability indices to be used in the design of power distribution networks in oil and gas plants*

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ABSTRACT: *The cost of loss of production in oil and gas plants is on average 6.5 times higher than that of plants in any other industry. Thus the reliability performance and analysis of oil and gas plants are unique. There have been many studies that have produced reliability indices for equipment that is used in industrial distribution networks, but these are all industry generic and none are specific to the oil and gas industry. This paper presents a set of equipment reliability indices that has been established from data collected from oil and gas plants and is suitable for use in reliability evaluations of the distribution networks of oil and gas plants. In the design of distribution networks for new oil and gas plants, engineers either do not have enough operational data, enough time or do not know how to perform the analysis required for establishing what type of network topology to use. This paper recommends the optimal network topology to use in such cases and provides evidence to support this proposal.*

KEYWORDS: Failure rate; mean time to repair; inherent availability; cost of loss of production; capital cost; total cost of ownership.

1 INTRODUCTION

Reliability is often discussed in terms of cost: the cost of loss in production and the damage that will result from a lack of reliability versus the cost of improved reliability. It is impossible to build a plant that has 0% chance of failure. The closer one gets to reaching zero, the greater the capital required. The challenge of reliability studies is to find the point at which the cost of the improved reliability of a plant added to the potential cost of failure is at its minimum. This is shown in figure 1 (Billinton & Allen, 1992a).

The cost of loss of production is important to the profitability of an oil and gas plant. Table 1 shows the one-hour interruption costs for plants in various industries. These values are based on a University of Saskatchewan survey and are presented in 2001 dollars. The interruption cost for one hour of a crude

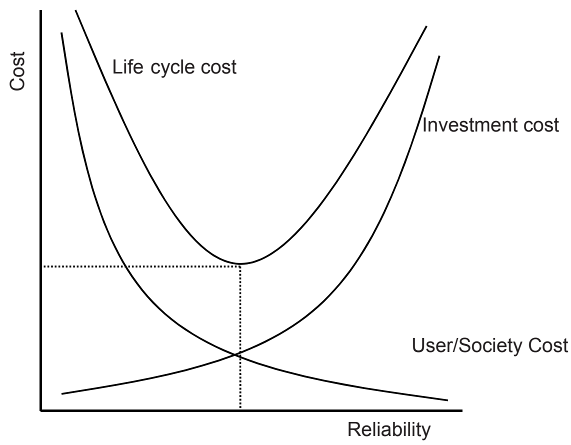

Figure 1: Cost of reliability and failure (Billinton & Allen, 1992a).

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Table 1: One-hour interruption costs for industrial consumers (Brown, 2002).

Industry	$/kW$_{peak}$
Logging	2.11
Mining	3.00
Crude petroleum	276.01
Quarry and sand	5.33
Services to mining	2.13
Food industries	20.46
Beverage industries	1.55
Rubber products	1.80
Plastic products	2.91
Leather products	1.37
Primary textiles	17.29
Textile products	8.93
Clothing	8.68
Wood industries	2.93
Furniture	23.20
Paper products	7.52
Printing and publishing	6.01
Primary metal	3.54
Fabricated metal	8.41
Machinery	7.70
Transportation	42.96
Electrical products	8.78
Non-metal minerals	9.59
Chemical products	4.65
Other manufacturing	15.31
Average industrial	8.40

petroleum plant in 2001 is given as $276.01/kW and the interruption cost for industrial plants on average is $8.40/kW. Thus the cost of loss of production is almost 33 times higher in oil and gas plants than the average industrial plant and 6.5 times higher than the next highest industry, ie. transportation.

In oil and gas plants reliability is important in terms of cost and safety. This is due to the hazardous environment that is created by the oil and gas processes. It is this potentially disastrous aspect of oil and gas plants that highlights the importance of reliability. It is important to gain a better understanding of the levels of reliability required at oil and gas plants, and how to achieve them.

There have been many studies that have produced reliability indices for equipment that is used in industrial and utility distribution networks, but these are all industry generic and none are specific to the oil and gas industry (Ying, 2009; Koval 1996).

This paper presents a set of reliability indices for equipment used in the distribution network of an oil and gas plant. Practical data is obtained from actual plants. Furthermore, the optimal network topology to be used in the design of a distribution network in an oil and gas plant is proposed. The network topology that is used by a particular existing plant is compared to alternative network topologies to establish which topology is optimal in terms of reliability.

1.1 Reliability indices

In order to calculate failure rate for all the various types of equipment that are used in the electrical distribution network, it is necessary to know exactly how many items of each type are installed in this distribution network. This is achieved by counting all the units of each type of equipment that are shown on the single line diagrams of the distribution network.

The indices can be calculated once the following is established:

- N = total number of units of a particular type of equipment
- T_p = the total period over which reliability data has been collected,
- T_f = the total number of failures of a particular type of component during that period, and
- R_{dt} = the repair down time (the total downtime for unscheduled maintenance for all the components of a particular type added together):

Failure rate (λ) is often expressed as failures per year per component or failures per unit year. It is calculated using the formula (Billinton & Allen, 1992a):

$$\lambda = T_f/NT_p \quad (1)$$

Mean time to repair ($MTTR$) is the average time to repair, replace or maintain a component after it has failed in service, expressed in hours per failure. It is calculated using the formula:

$$MTTR = R_{dt}/T_f \quad (2)$$

Mean time between failures ($MTBF$) is the mean exposure time between consecutive failures of a component. It is calculated using the formula:

$$MTBF = NT_p/T_f \quad (3)$$

Mean time to failure ($MTTF$) is the mean exposure time between the repair of a component and the next failure of that component. It is calculated using the formulae:

$$MTTF = MTBF(NT_p - R_{dt})/T_p \quad (4)$$

or

$$MTTF = MTBF - MTTR \quad (5)$$

In some instances the $MTTR$ is so small compared to the $MTBF$ that the $MTTR$ becomes negligible. Then

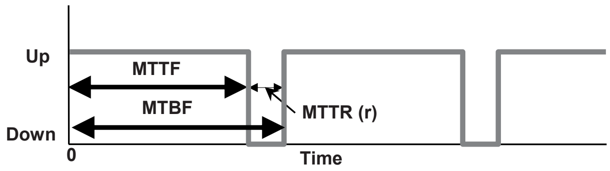

Figure 2: The relationship between *MTTF*, *MTBF* and *MTTR* (Billinton & Allen, 1992b).

MTBF = *MTTF*. Figure 2 shows the relationship between *MTTF* and *MTBF*.

Inherent availability (A_i) is the probability that a component or a system will be up or down. A_i considers only downtime for repair to failures. A_i is calculated using the formula:

$$A_i = MTTF/(MTTF + MTTR) \quad (6)$$

These indices can be used as inputs into a software based reliability model. It is important to compare the calculated equipment reliability indices with those given by the IEEE Gold Book (IEEE Standards Board, 2007) to validate the calculated indices. Where there is insufficient reliability data to compile these equipment reliability indices, the equipment reliability indices that are given in the IEEE Gold Book (IEEE Standards Board, 2007) are used.

1.2 Network topology

A particular plant whose cost of loss of production is well understood is selected. The average cost of loss of production for the chosen plant is established. The capital costs of increasing the reliability of the power supply to this plant and the savings that are associated with a lower level of reliability are also established.

1.2.1 Cost of loss of production

In utility distribution networks, the monetary cost of loss of production is frequently limited to the cost of non-supplied energy (Cossi et al, 2012).

Most oil and gas and gas to liquid plants are made up of a number of plants that convert feed stocks into products by means of chemical and mechanical processes. The plants follow each other in terms of a process flow whereby the products of one plant form the feedstock of the next plant.

If the entire power supply to a plant is interrupted the plant will not continue to operate. This is typically what happens if there is a failure in the distribution network that feeds power to the plant. Usually such a failure results in a loss of production.

The cost of loss of production differs within a factory. The reason for this is that the different plants produce products in different quantities and that have different economic values. Also, the plants that are downstream in the process rely on the plants upstream for their feed stocks. If an upstream plant fails, the impact of its failure is cascaded downstream. The cascading effects of the failure of upstream plants are mitigated by the fact that many plants have a storage buffer of either their feed stocks or their products. This means that if an upstream plant only fails for a short period of time, it is possible that the downstream plants may still have enough feedstock to ride through the failure of the upstream plant. If the upstream plant is not brought online quickly enough, the downstream plants will stop producing product. This cascading effect must be taken into account when calculating the cost of loss of production for a particular plant.

The cost of loss of production that results from a power failure also includes the financial savings that result from electrical energy not being consumed by the failed plant during its down time. The cost of loss of production also includes any costs that may be associated with damage that may result from a loss of power. An example of such a situation would be solidification of heated liquid wax in a pipeline if it is allowed to cool in the pipeline due to a loss of power. The cost of loss of production takes into account the cost of cleaning out the pipe, as well as the cost of the production time that is lost while the pipe is unclogged.

1.2.2 Capital cost of increased reliability

Increasing reliability through design is usually associated with installing more equipment, thereby increasing the number of possible paths for electric current to flow through (Samui et al, 2012). The capital cost of increased reliability is established by obtaining quotes from vendors for the supply and installation of power distribution equipment.

1.2.3 Reliability analysis

The availability of the point of interest in the distribution network (possibly the reticulation substation of a particular plant) is established by modelling the distribution network up to that point using a software package. This value for the availability of the point of interest is converted into the number of hours of downtime per year and multiplied by the average cost of loss of production per hour in order to arrive at an expected cost of loss of production per year.

Once this cost of loss of production per year has been established, the present value (PV) of this calculated annual loss of production over the life of the plant is added to the capital cost of building a particular network topology. The resulting value is the cost of ownership of the plant only with regards to the reliability of the design of the distribution network.

When comparing the cost of ownership of alternative topologies the best method is to compare the total cost of each alternative topology. Another common method is to find the incremental cost in all alternatives over a base, or least expensive topology. Using the incremental cost method may introduce a slight error into the economic comparisons, thus the total cost method is used.

One more point that is worth noting is the fact that the distribution network that feeds the point of interest is only a very small portion of a very large distribution network. When calculating the capital cost of a network topology only the components that make up the distribution network that a feed point of interest are included. This is to prevent the capital cost of building the entire network from skewing the results of the economic analysis. The capital costs associated with building the whole network would be disproportionately greater than the cost of loss of production at the point of interest.

2 CALCULATION OF EQUIPMENT RELIABILITY INDICES

The reliability indices that are calculated for the existing plants are compared to the reliability indices that are given in the IEEE Gold Book (IEEE Standards Board, 2007) in table 2.

A factor of 10 is chosen to be the acceptable limit of deviation for the calculated equipment reliability indices to deviate from the equipment reliability indices that are given by the IEEE Gold Book. While a factor 10 may seem lenient, it is in fact an acceptable limit of deviation as there are numerous factors that could influence the failure rates and *MTTR*s of equipment in different plants.

The indices given in the IEEE Gold Book represent the industry average and it is possible the existing plants' reliability performance are above, or below the industry average. Thus the comparison between the reliability indices that are calculated for existing factory and the indices given in the IEEE Gold Book can more accurately be described as a sanity check to see that the calculated values are probable.

In light of the comparison that is made between the indices that are calculated for the existing factory and the indices that are given by the IEEE Gold Book, the indices that should be used in the reliability analysis of the distribution networks of oil and gas plants are given in table 3.

3 OPTIMAL NETWORK TOPOLOGY

3.1 Cost of loss of production

The failures of existing Plant A that have occurred in the 19-year period over which data has been collected are listed.

The list only includes the failures in the portion of the distribution network between distribution substation 2JJ-DS-1 and the reticulation substation for the Plant A, 2M3-SS-8 (figure 3). There have been instances where the entire Plant A has been down due to mechanical failures that have been significant enough to cause the shutdown of the whole plant. In addition, there have been instances where all the loads feeding from distribution substation 2JJ-DS-1 have been lost due to a fault in the network feeding 2JJ-DS-1. There have also been instances where the utility supply has failed and the whole factory has been down.

In this study we are only interested in the recorded cost of loss of production for downtime of the Plant A. Only the information regarding the downtimes of the Plant A as a result of a failure of the electrical distribution network is taken into account.

Table 2: Comparison between equipment reliability indices calculated plant data and those given by the IEEE Gold Book (IEEE Standards Board, 2007).

Equipment	Equipment sub-class	Failure rate IEEE Gold Book	Failure rate calculated from data	Factor of deviation	MTTR (h) IEEE Gold Book	MTTR (h) calculated from data	Factor of deviation
Bus ducts	All voltages	0.000410	0.000139	2.96	9.5	–	–
Cables	601-15,000 V	0.020243	0.016388	1.24	35.0	4.00	8.75
	Above 15,000V	0.011024	0.027993	0.39	16.0	29.40	0.54
Cable terminations	All voltages	0.000303	0.001303	0.23	23.4	6.75	3.47
Circuit breakers	Above 600 V	0.003600	0.008469	0.43	168.0	11.00	15.27
Generators	All	0.169100	0.015789	10.71	32.7	29.10	1.12
Switchgear busses	Above 600 V	0.001917	0.003244	0.59	36.0	6.60	5.45
Transformers	Liquid filled	0.015300	0.026027	0.59	1178.5	6.70	175.90
Utilities	–	–	0.250000	–	–	2.50	–

Table 3: Reliability indices that should be used for reliability analysis of oil and gas plants.

Equipment	Equipment sub-class	Failure rate (failures per unit year)	Source of failure rate	MTTR (h)	Source of MTTR
Bus ducts	All	0.000139	Calculated	9.50	IEEE Gold
Cables	Critical power	0.016388	Calculated	4.00	Calculated
	Normal power	0.027993	Calculated	29.40	Calculated
Cable terminations	All	0.001303	Calculated	6.75	Calculated
Circuit breakers	All	0.008469	Calculated	11.00	Calculated
Generators	All	0.169100	IEEE Gold	29.10	Calculated
Switchgear busses	All	0.003244	Calculated	6.60	Calculated
Transformers	All	0.026027	Calculated	6.70	Calculated
Utilities	All	0.250000	Calculated	2.50	Calculated

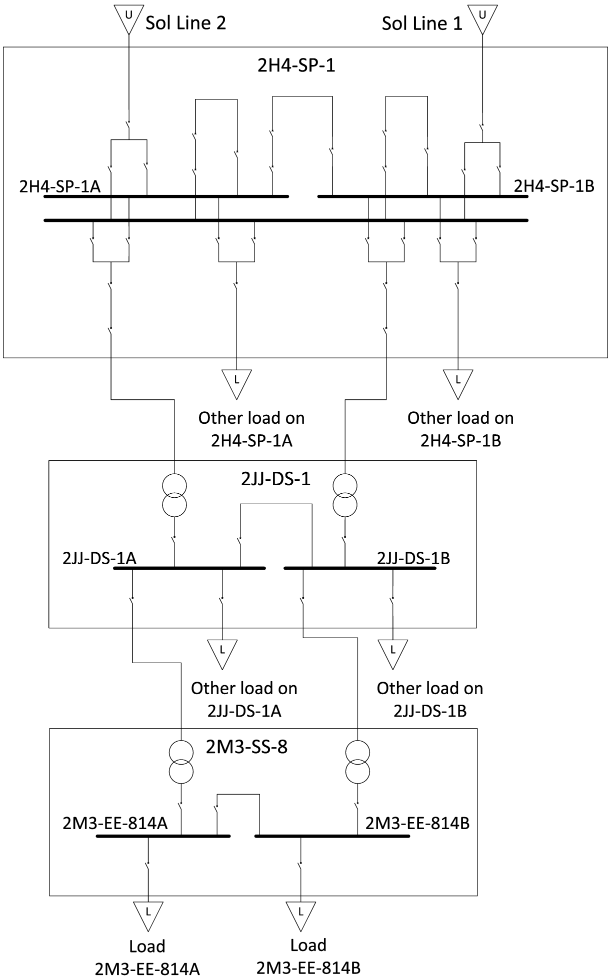

Figure 3: Single line diagram of existing distribution network that feeds 2M3-SS-8.

In order to calculate the average cost of loss of production for the Plant A, the first step is to convert the cost of loss of production values into PVs. This is because the failures that have resulted in losses in production have occurred in different years and due to the time value of money, these values are not comparable.

PV is calculated as follows:

$$PV = val(1 + r)^{a} \quad (7)$$

where *val* = the value of the cost of loss of production in the year that it occurred; *r* = the rate of return or inflation rate (chosen to be 10%); and *n* = the number of periods (years) that have passed since the failure.

The average cost of loss of production is:

$$C_{ave} = \sum C_{trip} / \sum P_{trip} \quad (8)$$

where C_{trip} = the cost of loss of production for each trip, and P_{trip} = the total period of down time for each trip.

Thus for the Plant A (which has a load of 14 MW), the average cost of loss of production in 2010 is $805,425.64 per hour. This equates to an hourly cost of loss of production of $57.53/kW.

3.2 Capital costs associated with increased reliability

The costs of the equipment that would be required to increase the reliability of a distribution network in 2010 equivalent prices are estimated. An attempt has been made to include the costs of installation and peripheral materials such as plinths and cable racking associated with each item of equipment.

3.3 Influence of network topology

The existing distribution network topology is analysed and compared to alternative topologies presented in the IEEE Gold Book. The existing distribution network that feeds 2M3-SS-8 (the reticulation substation for the Plant A) is shown in figure 3. In this topology the cables and transformers are designed in such a way that each feeder can carry the load of the entire board that it is feeding with the bus coupler closed. The bus couplers are kept open under normal operating conditions so that each section of each board has a feeder connection that is only carrying half the load of the board.

In Alternative Topology 1, only the bare minimum is installed in terms of equipment. The single line diagram for this topology is shown in figure 4. In this topology the cables and transformers are designed in such a way that each feeder can carry the load of the entire board that it is feeding. There are no bus couplers that split the boards in two, thus there is no redundancy of supply.

In Alternative Topology 2, a second utility feeder is added to Alternative Topology 1. The single line diagram for this topology is shown in figure 5. Each utility feeder is designed in such a way that it can carry the load of 2H4-SP-1A and 2H4-SP-1B at the same time with the bus coupler closed. The bus coupler between 2H4-SP-1A and 2H4-SP-1B is open under normal operating conditions.

In Alternative Topology 3, a hospital bus is added to the consumer substation 2H4-SP-1 of Alternative Topology 2. The single line diagram for this topology is shown in figure 6. The hospital bus is only connected to the circuit when one of the bus sections (2H4-SP-1A or 2H4-SP-1B) is being maintained. This allows complete isolation of the bus section that is being worked on without loss of power to any load. Normal operation is the same as that described for Alternative Topology 2.

In Alternative Topology 4, a second feeder is added between consumer substation 2H4-SP-1 and distribution substation JJ-DS-1 and the bus in JJ-DS-1 is spilt in two with a bus coupler. The single line diagram for this topology is shown in figure 7. For the boards that have bus couplers (2H4-SP-1 and 2JJ-DS-1) the cables and transformers are designed in such a way that each feeder can carry the load of the entire board that it is feeding with the bus coupler closed. The bus couplers are kept open under normal operating conditions so that each section of each board has a feeder connection that is only carrying half the load of the board. There is only one feeder to 2M3-EE-814A, thus no form of redundancy of supply to 2M3-EE-814A.

The results from the reliability analyses and cost calculations are summarised in table 4 and illustrated on a graph in figure 8.

Alternative Topology 1 is the most basic topology with the minimum amount of equipment required to supply power to reticulation substation 2M3-SS-8. As would be expected, it is also the topology with the lowest capital cost and greatest cost of loss of production over the life of the plant.

In Alternative Topology 2, an additional utility supply is added to the consumer substation 2H4-SP-1. This results in a significant increase in availability compared to Alternative Topology 1 with an increase

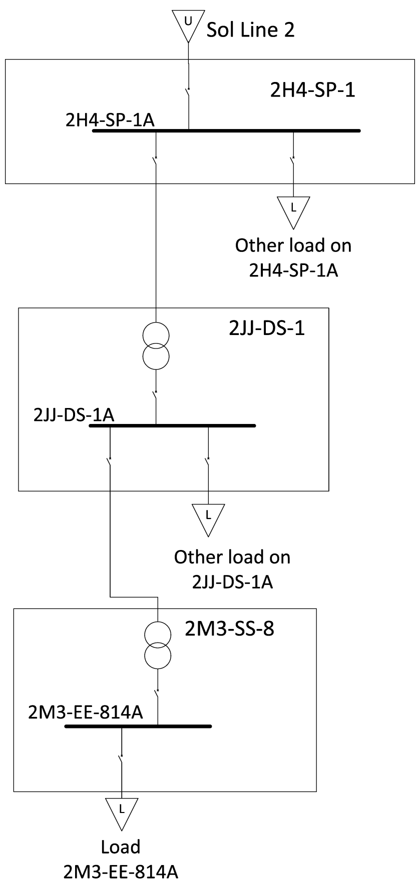

Figure 4: Single line diagram of Alternative Topology 1.

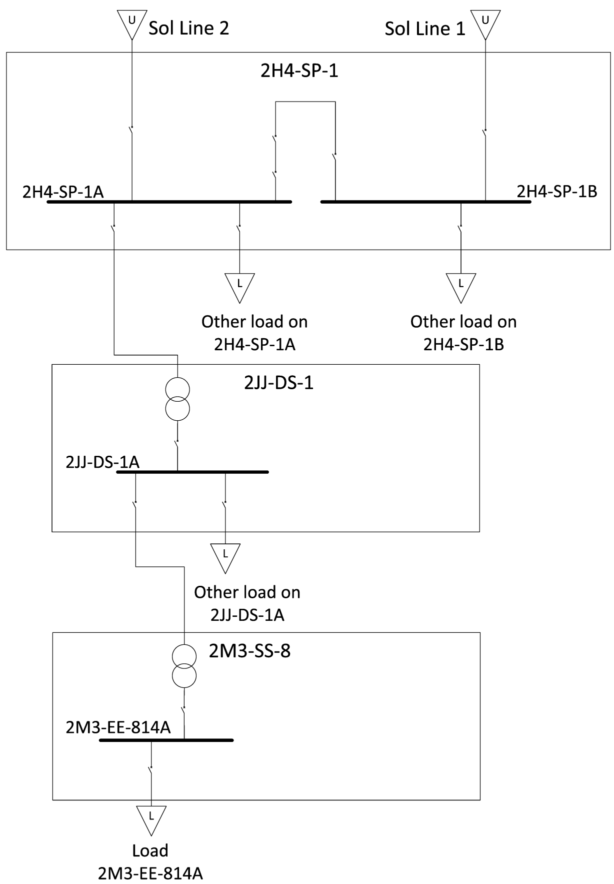

Figure 5: Single line diagram of Alternative Topology 2.

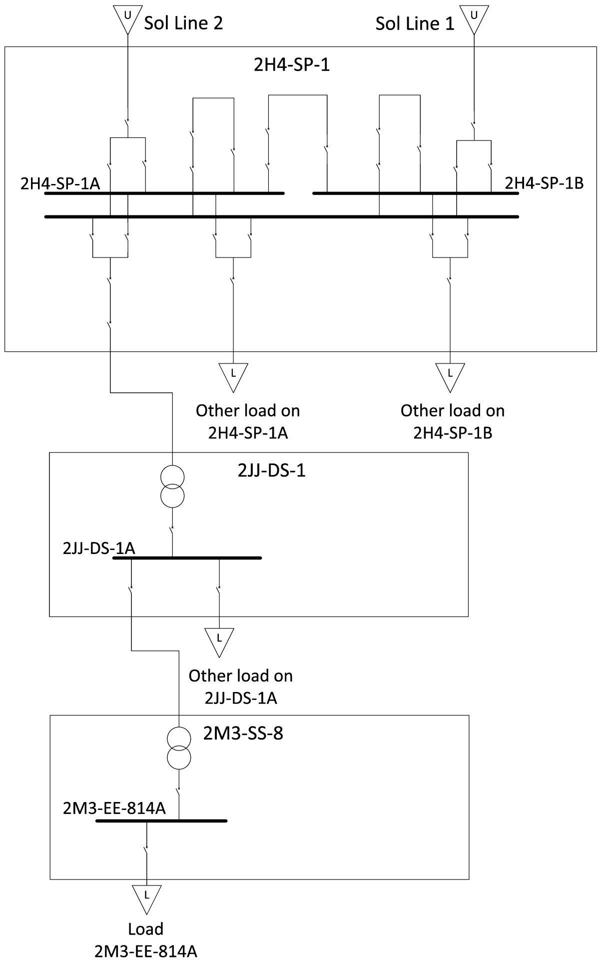

Figure 6: Single line diagram of Alternative Topology 3.

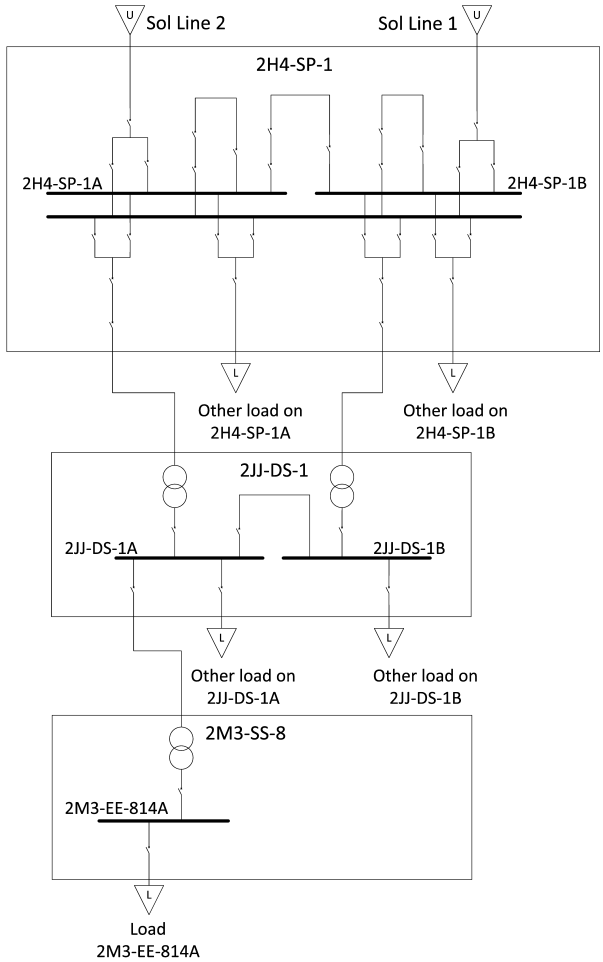

Figure 7: Single line diagram of Alternative Topology 7.

Table 4: Results from reliability analysis and cost calculations.

Distribution network topology	Availability (%)	Capital cost	Cost of loss of production	Cost of ownership	Cost of ownership (pu)
Alternative Topology 1	99.95431	$7,241,414.40	$161,183,551.01	$168,424,965.41	3.26
Alternative Topology 2	99.97189	$9,585,734.40	$99,165,454.56	$108,751,188.96	2.11
Alternative Topology 3	99.97083	$18,671,558.40	$102,904,884.72	$121,576,443.12	2.35
Alternative Topology 4	99.98220	$22,946,668.80	$62,794,204.60	$85,740,873.40	1.66
Existing feed to 2M3-SS-8	99.99252	$25,270,924.80	$26,387,676.99	$51,658,601.79	1.00

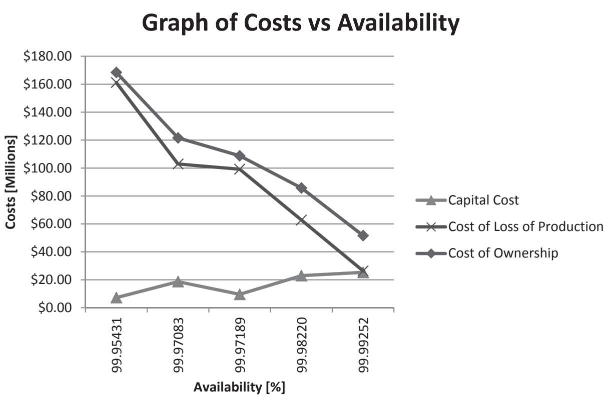

Figure 8: Graph of costs associated with reliability as a function of availability.

in capital cost of only $2.35 million (although the additional capital cost does not consider the cost to the utility for creating the additional power supply). The increase in availability results in a decrease in loss of production costs of $62 million over the life time of the plant. This results in a decrease in cost of ownership to the value of $59.6 million. Thus the investment in a second utility power supply is extremely good value for money.

In Alternative Topology 3 a hospital bus is added to consumer substation 2H4-SP-1 along with a complicated system of switches and circuit breakers to allow the hospital bus to be utilised when it is required and to allow the protection system to operate correctly in the event of a fault.

While the addition of the hospital bus does allow for more pathways that current can flow along to reach the distribution substations, each of these new pathways includes a number of extra circuit breakers and switches in series. Since the reliability of these circuit breakers is not perfect, the resulting system has a slightly lower availability than Alternative Topology 2. Alternative Topology 3 costs almost twice the price of Alternative Topology 2 to build. Thus, while the cost of loss of production for the two systems only differs by $3.6 million, the total cost of ownership for Alternative Topology 3 is $128.27 million.

This means that unless the hospital bus is installed to allow work to be done to certain parts of the substation without shutting the whole substation down, there is no benefit associated with the addition of a hospital bus. Furthermore, it is very expensive.

In Alternative Topology 4 an additional cable is installed between consumer substation 2H4-SP-1 and distribution substation 2JJ-DS-1 along with an associated additional transformer and incomer into the distribution board in 2JJ-DS-1. The board in 2JJ-DS-1 is also split into two with a bus coupler.

This results in a moderate improvement in availability over both Alternative Topologies 2 and 3. The cost of Alternative Topology 4 is $4.27 million more than that of Alternative Topology 3 and the associated cost of loss of production is $49.73 million less than that associated with Alternative Topology 2. The result is a total cost of ownership that is $35.87 million less than that of Alternative Topology 3 and $23.07 million less than that associated with Alternative Topology 2. Thus the addition of the second path from the consumer substation to the distribution substation is a good investment.

The existing topology of the feed to 2M3-SS-8 is very similar to Alternative Topology 4, except for the addition of a second path from distribution substation 2JJ-DS-1 to reticulation substation 2M3-SS-8. This results in a moderate improvement in reliability over Alternative Topology 4 and is just over $2.32 million more expensive to build. The result is a $36.4 million saving in the cost of loss of production and a $34.1 million saving in the total cost of ownership over the lifetime of the plant. Thus the addition of the second path from distribution substation 2JJ-DS-1 to reticulation substation 2M3-SS-8 is also a good investment.

It is clear from the discussion above that the existing topology is the most economically viable one with the lowest total cost of ownership in terms of reliability over the lifetime of the plant. The single improvement that is the most valuable in attempting to increase the reliability of the distribution network is the addition of a second utility supply.

At an availability of 99.99252% (which is achieved by the existing topology), the graph of Cost of Ownership versus Availability trends downwards. This implies that there is still room for improving the reliability of the plant through increased capital expenditure. However, since the existing topology is already representative the most conservative distribution topology commonly used (ie. the dual radial network topology) it is unlikely that any incremental improvement to the design of the topology would be practical.

Further improvements in the availability should be achieved through purchasing better quality equipment that have lower failure rates and/or equipment that require shorter repair times. It is important to note that this study only considers the impact of design on the reliability of distribution networks. Availability could be greatly increased by adopting conservative maintenance plans and keeping a conservative inventory of spares.

4 SENSITIVITY ANALYSIS

4.1 Cost of loss of production

So far in this paper an increase in availability results in a decrease in total cost of ownership because the cost of loss of production of the plant that has been studied is so high. According to table 1 the one hour interruption cost for a primary metals plant is $3.54/kW. This translates into $8.35/kW/h in 2010. If a primary metals plant of similar size to Plant A (14 MW) was analysed, its cost of loss of production would be $116,900 per hour and the results of the reliability analysis and cost calculations would be as per table 5 and figure 9.

Table 5: Results of reliability analysis and cost calculations for plant with lower cost of loss of production.

Distribution network topology	Availability (%)	Capital cost	Cost of loss of production	Cost of ownership	Cost of ownership (pu)
Alternative Topology 1	99.95431	$7,241,414.40	$23,386,257.79	$30,627,672.19	1.05
Alternative Topology 2	99.97189	$9,585,734.40	$14,387,999.70	$23,973,734.10	0.82
Alternative Topology 3	99.97083	$18,671,558.40	$14,930,556.79	$33,602,115.19	1.15
Alternative Topology 4	99.98220	$22,946,668.80	$9,110,864.27	$32,057,533.07	1.10
Existing feed to 2M3-SS-8	99.99252	$25,270,924.80	$3,828,610.38	$29,099,535.18	1.00

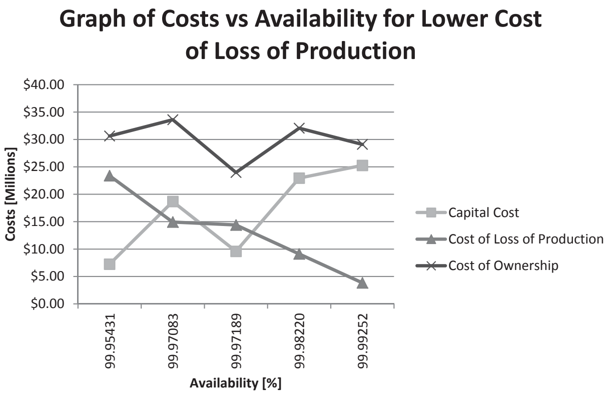

Figure 9: Graph of the costs associated with reliability for of a plant that has a lower cost of loss of production.

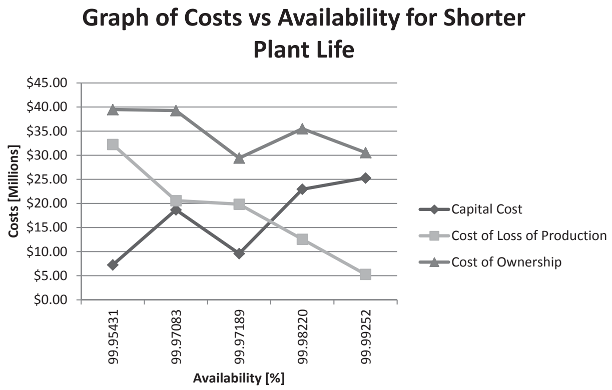

Figure 10: Graph of the costs associated with the reliability of a plant that has a shorter life of plant.

Table 6: Results for reliability analysis and cost calculations of a plant with a shorter life of plant.

Distribution network topology	Availability (%)	Capital cost	Cost of loss of production	Cost of ownership	Cost of ownership (pu)
Alternative Topology 1	99.95431	R 7,241,414.40	R 32,236,710.20	R 39,478,124.60	1.29
Alternative Topology 2	99.97189	R 9,585,734.40	R 19,833,090.91	R 29,418,825.31	0.96
Alternative Topology 3	99.97083	R 18,671,558.40	R 20,580,976.94	R 39,252,535.34	1.28
Alternative Topology 4	99.98220	R 22,946,668.80	R 12,558,840.92	R 35,505,509.72	1.16
Existing feed to 2M3-SS-8	99.99252	R 25,270,924.80	R 5,277,535.40	R 30,548,460.20	1.00

From figure 9 it can be seen that Alternative Topology 2 is the optimal solution in terms of total cost of ownership. The capital cost associated with increasing the availability of the plant above 99.97189% is not justified by the associated saving in terms of the decreased cost of loss of production over the life of the plant. The basic shape of the graph in figure 9 is similar to that of the graph in figure 1. The optimal solution is in the middle of the graph as opposed to one of the ends.

4.2 Life of plant

While the average cost of loss of production has been calculated from data that has been collected regarding the trips that have occurred in the Plant A over the past 19 years, there are some values on which this study is based that have been assumed. One such value that is assumed is the life of the plant.

The cost comparisons that are shown in table 4 are based on a life of plant of 50 years. If a life of plant of 10 years had been assumed, the results of the cost comparison would be as per table 6 and figure 10.

These results shown in table 6 and figure 10 are very similar to those which are given in table 5 and figure 9. This is because in the same way that a lower average cost of loss of production results in a lower cost of loss of production over the life of the plant, so too does a shorter plant lifespan result in a lower cost of loss of production over the life of the plant. Thus, the shape of the graph in figure 10 is very similar to that in figure 9 and as in the case with the lower average cost of loss of production; Alternative Topology 2 is the optimal solution for a plant with a shorter lifespan.

It is therefore, important to note that the conclusions that are drawn in this paper are based on an assumed value that cannot be objectively quantified, ie. the life of the plant. This assumption is based on the fact that the existing factory has been in operation for over 30 years. At the time that this study is being undertaken the same factory is expected to be in operation for at least 20 years into the future. At the very least, it should be kept in mind that while the plant is expected to be operational for 50 years, many (or most) of the components that make up the plant will not last 50 years. These will be replaced as they fail.

The cost comparisons that are made in this paper do not take the replacement costs of these components into consideration.

4.3 Improved reliability

Table 7 and figure 11 show the results of the cost calculations for the network topologies shown in table 4 and figure 8. They also show seven additional topologies of higher reliability that have been mathematically extrapolated.

The availability of each of the additional topologies is calculated by increasing the availability of each

Table 7: Results of cost calculations of initial network topologies plus seven topologies of higher reliability.

Distribution network topology	Availability (%)	Capital cost	Cost of loss of production	Cost of ownership	Cost of ownership (pu)
Alternative Topology 1	99.95431	$7,241,414.40	$161,183,551.01	$168,424,965.41	3.26
Alternative Topology 2	99.97189	$9,585,734.40	$99,165,454.56	$108,751,188.96	2.11
Alternative Topology 3	99.97083	$18,671,558.40	$102,904,884.72	$121,576,443.12	2.35
Alternative Topology 4	99.98220	$22,946,668.80	$62,794,204.60	$85,740,873.40	1.66
Existing feed to 2M3-SS-8	99.99252	$25,270,924.80	$26,387,676.99	$51,658,601.79	1.00
Additional Topology 1	99.99686	$32,852,202.24	$11,088,753.65	$43,940,955.89	0.85
Additional Topology 2	99.99868	$42,707,862.91	$4,659,768.17	$47,367,631.09	0.92
Additional Topology 3	99.99944	$55,520,221.79	$1,958,149.68	$57,478,371.47	1.11
Additional Topology 4	99.99977	$72,176,288.32	$822,862.86	$72,999,151.18	1.41
Additional Topology 5	99.99990	$93,829,174.82	$345,787.30	$94,174,962.12	1.82
Additional Topology 6	99.99996	$121,977,927.26	$145,308.36	$122,123,235.63	2.36
Additional Topology 7	99.99998	$158,571,305.44	$61,062.16	$158,632,367.61	3.07

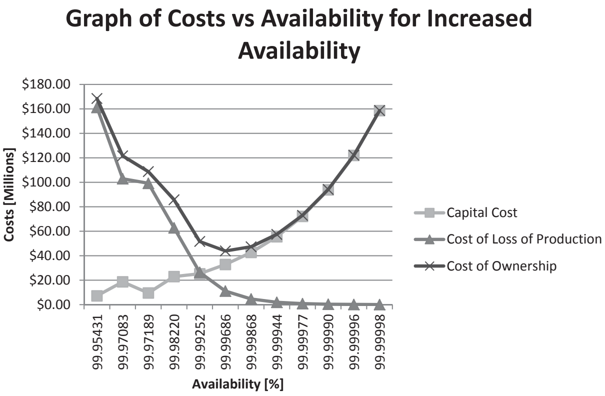

Figure 11: Graph of cost calculations of initial network topologies plus seven topologies of higher reliability.

consecutive additional topology by 58% starting with the topology that is currently being used in Plant A. The greatest improvement in availability that was achieved by improving the topologies discussed in table 4 is 58%.

The capital cost of each of the additional topologies is calculated by increasing the capital cost of each consecutive additional topology by 30% starting with the topology that is currently being used in Plant A. The average increase in capital cost that was associated with improving reliability of the topologies discussed in table 4 is 30%.

The data in table 7 and figure 11 show that by increasing the availability of the distribution network by one increment, either by the use of more reliable components or by the use of even more conservative design, an even lower cost of ownership can be achieved. However, the data also shows that by increasing the investment more than that (and thus, the network reliability) the cost of ownership starts to increase.

Figure 11 shows that the optimal expenditure on reliability is achieved in Additional Topology 1. This is an extrapolated value that is impractical to achieve through design. In reality, the cost of ownership represented by Additional Topology 1 could possibly be achieved by building a dual radial network with superior quality equipment and instituting a very conservative maintenance plan.

Extrapolating the costs and benefits associated with topologies that achieve greater availability illustrates that the investment in improving reliability does reach a point where the investment bares no advantage. Figure 11 has exactly the same shape the graph in figure 1.

5 CONCLUSIONS

The set of equipment reliability indices that are calculated in this paper are compared to equivalent reliability indices that are given by the IEEE Gold book and are found to be similar. It is therefore concluded that they are suitable for use in the reliability evaluation of the distribution networks of oil and gas plants.

The distribution network topology of an existing plant has been compared to several other commonly used network topologies in terms of the lifetime costs associated with reliability of each topology.

It has been found that the dual radial network topology is the optimal topology because it is associated with the lowest total cost of ownership in terms of reliability. It has also been established that incremental additional expenditure that would increase the reliability of the distribution network would most likely result in a saving in total cost of ownership over the lifetime of the plant.

The paper only considers the impact of design on the reliability of a distribution network. Thus the additional investment that could improve the reliability (and thus the total cost of ownership) could be in the form of adopting a conservative maintenance philosophy as well as the establishment of a conservative spares inventory.

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