ANALYSIS OF LOSS REDUCTION TECHNIQUES FOR LOW VOLTAGE DISTRIBUTION NETWORK

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ABSTRACT: Energy losses in a typical distribution system can be in a range of 6 to 10%, and it depends on the system characteristics, installed equipment, and operating strategies of the distribution network. Losses reduction during peak periods needs special attention since the losses in the system and the cost of the losses are the highest during this peak. Distribution System Owner (DSO) always strives to reduce power losses in the distribution network that eventually leads to energy saving and cost reduction. This paper presents the model of a selected 33 kV, 11 kV and LV network of a representative primary substation, which is a part of the Muscat Electricity Distribution Company (MEDC) network. In order to quantify the losses in various components, the numerical simulation is carried out using the ETAP software package. The technical losses, power factors, and voltage profiles are quantified and analyzed. This paper also investigates on the optimal conductor and cable selection for 11kV lines, capitalization values for transformer losses to alleviate system losses and hence the system operational cost. The method of determining optimal conductor and cable size for an 11kV distribution network is presented, where the cost of losses for various conductors with their extra construction or material cost are compared. It also presents the detailed model of calculating capitalization values for distribution transformer losses and sample calculation of the capitalization values. Utilizing these capitalization values, the transformer buyer can calculate the total life cycle cost of the distribution transformers and select the most economical one.

Keywords: Distribution network; Loss reduction method; System modelling; Optimal conductor selection; Capitalization values.

تحليل تقنيات الحد من خسائر الطاقة لشبكة توزيع الجهد المنخفض

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الملخص: يمكن أن تتراوح خسائر الطاقة في نظم التوزيع من 6 إلى 10٪، وتعتمد على خصائص النظام والمعدات المركبة واستراتيجيات التشغيل لشبكة التوزيع. يحتاج تخفيض الخسائر خلال فترات الذروة إلى اهتمام خاص حيث أن الخسائر في النظم وتكلفة الخسائر هي الأعلى خلال هذه الذروة. يسعى مالك نظام التوزيع دائمًا لتقليل فقد الطاقة في شبكة التوزيع مما يؤدي في النهاية إلى توفير الطاقة وخفض التكلفة. تقدم هذه الورقة نموذج شبكة مختارة بجهد 33 كيلوفولت و 11 كيلوفولت و415 V من محطة فرعية وهي جزء من شبكة شركة مسقط لتوزيع الكهرباء. من أجل تحديد الخسائر في المكونات المختلفة ، يتم إجراء المحاكاة العددية باستخدام حزمة برنامج ETAP. يتم تحديد وتحليل الخسائر التقنية وعوامل الطاقة وملامح الجهد. تبحث هذه الورقة أيضًا في الموصل الأمثل واختيار الكابلات لخطوط 11 كيلو فولت ، والقيم الرأسماليّة لخسائر المحولات للتخفيف من خسائر النظام وبالتالي التكلفة التشغيلية للنظام. يتم تقديم طريقة تحديد الموصل الأمثل وحجم الكابل لشبكة توزيع 11 كيلو فولت ، حيث تتم مقارنة تكلفة الخسائر لمختلف الموصلات بتكلفة البناء أو المواد الإضافية. يتم عرض النموذج التفصيلي لاحتساب قيم الرأسماليّة لخسائر محولات التوزيع، ويتم توفير حساب عينة منها. باستخدام قيم الرأسماليّة هذه، يمكن لمشتري المحولات حساب التكلفة الإجمالية لدورة الحياة لمحولات التوزيع واختيار الأكثر اقتصاداً.

الكلمات المفتاحية: شبكة توزيع؛ طريقة الحد من الخسارة؛ نمذجة النظام؛ اختيار الموصل الأمثل؛ قيم الرأسماليّة.

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NOMENCLATURE

I	Current flowing through the cable/conductor in Ampere
N	Number of months in a year
P	Total peak losses in three-phase lines in kW
H	Number of hours in a year
R	Resistance of the cable in Ohm/km
X	No-load losses capitalization value in OMR/W
Y	Load losses capitalization value in OMR/W.
η_T	Transmission efficiency
θ_{ki}	*Y*-bus elements angle in radian
δ_k, δ_i	Voltage angles in radian
$\lvert V_i \rvert$	Voltage magnitude at the i^{th} bus in per unit
$\lvert V_k \rvert$	Voltage magnitude at the k^{th} bus in per unit
$\lvert Y_{ki} \rvert$	The Magnitude of *Y*-bus elements in per unit
DSO	Distribution system owner
LF	Load factor
MEDC	Muscat Electricity Distribution Company
C_{ACC}	Annual carrying charge on extra construction
C_{AS}	Cost of annual loss savings in OMR
C_{DC}	Annual demand cost in OMR/kW
C_e	Levelized cost of energy in OMR/kWh
C_{EC}	Annual energy cost of peak losses OMR/kW
C_{kwh}	Cost of unit energy in OMR/kWh
$C_{Net,AS}$	Net annual savings in OMR
C_{sc}	System capacity cost in OMR
C_{TAC}	Total annual cost for peak losses in OMR
$C_{TAC/kW}$	Total annual cost for per kW peak losses in OMR
$C_{TAC,PS}$	Total annual loss cost of a particular size of the conductor in OMR
$C_{TAC,SS}$	Total annual loss cost of the smallest size conductor in OMR
C_{WEC}	Wholesale electricity purchase cost per month in OMR/kW
I_F	Increasing factor
L_f	Loss factor
P_{pl}	Uniform annual peak load factor
P_k	Real power at the k^{th} bus
$P_{loss,ki}$	Real power losses between the *k*-*i* branches
Q_k	Reactive power at the k^{th} bus
$Q_{loss,ki}$	Reactive power losses between *k*-*i* branches
R_F	Peak responsibility factor
R_{fc}	Levelized annual fixed charge rate in OMR
$S_{loss,ki}$	Power losses between the *k*-*i* branches

1. INTRODUCTION

With the continuous growth in size and complexity of the power distribution network, reduction in losses can return significant savings for the Distribution System Owner (DSO). Losses reduction strategy provides other advantages, such as relief in system capacity, and the possibility of extending capital expenses for improving and expanding the system for the DSO (Emmanuel M *et al.* 2017). To meet load demand, distribution companies need to alleviate the system losses and enhance the quality of power supply to achieve social and economic development.

Losses associated with the distribution network categorize as technical and non-technical losses. In distribution networks, the fixed losses are in a range of 1/4 to 1/3 of the technical losses (Inan H *et al.* 2014). Such fixed losses occur due to corona, leakage current, dielectric losses, no-load losses, and current flow through measurement and control elements and realize as heat and noise. The variable losses represent 2/3 and 3/4 of the distribution losses and depend on the magnitude of the current flow (MEDC 2018). Such variable losses include the copper losses in the distribution lines and transformers. An increase in load demand causes an increase in current flow through the lines and the distribution transformers windings, and hence an increase in losses. Such losses are significant in distribution networks because of the involvement of a large number of distribution transformers. In addition, system unbalances due to unbalanced load at the consumer side increases losses in the transformer. A small amount of copper losses also contributes to the system due to the harmonic currents. However, the high-frequency harmonic voltage has a greater contribution to the core losses of the transformer (Al-Badi AH *et al.* 2011, Daut I *et al.* 2013).

Depending upon only the initial cost of the transformers is not an economical choice in buying the efficient distribution transformers. The losses in distribution transformers, especially the load loss occurs based on the load pattern, which is variable during its operational lifetime (Al-Badi AH *et al.* 2011). Therefore, the transformer buyer needs to evaluate the no-load and load losses capitalization values for their requisition transformers over the transformer lifespan. The capitalization values of the transformer depend on system capacity cost, Levelized cost of the energy, load profile and the economic consideration (Wijayapala WDAS *et al.* 2016). The detailed model of calculating capitalization values for distribution transformer losses are presented, and the model is applied to capitalization values for MEDC distribution transformers. Further, the distribution system losses can be alleviated by increasing the conductor size (Zhu Z *et al.* 2016). However, increasing the conductor size without engineering sense may increase the cost and losses. Therefore, an economic optimal conductor size needs to be selected. In this study, the differences in losses are not compared with the total material and labour costs for building/rebuilding the line; instead, the differences in the cost of losses for various conductors are compared with only construction costs above those required to build the line with the smallest suitable conductor.

The saving resulted from loss reduction does not only reflect on the financial aspect of the saved energy but also reflects on releasing the system capacity that can reduce the requirement of system development and lessen the deteriorating of system components. In the USA, the average losses in transmission and distribution systems are around 7.5%, whereas, the average losses in the distribution system only are about 6% (Inan H *et al.* 2014). The total losses in a distribution system for one of the distribution companies in Oman reached to 6.92% in 2018 (MEDC (2018)), which is very close to the reported percentage in the USA. The energy loss in the Main Interconnected System (MIS) in Oman reached 1.43% in 2018 (OETC 2019), which is well within international norms. In order to quantify the technical losses in MEDC distribution network, the model of a selected 33 kV, 11 kV and LV network of a representative primary substation is developed in this work. The distribution network components (transformer, cable, and load) model parameters are obtained from the concerned company using the system single-line diagrams (SLD). The transformer parameters include kVA rating, impedance ratio, and rated voltage. The cables are modelled using the cable type, length and cross-section area. The loads are modelled based on the collected data that is distributed in each feeder equally to all loads. ETAP software is used to implement and simulate the network model.

This introduction is followed by presenting the methods of minimizing losses in section 2. Section 3 presents the capitalization of losses for distribution transformers. Section 4 discusses the optimal conductor size selection for 11kV and LV networks. Modelling of a selected 3kV, 11kV and an LV network representative primary substation is presented in section 5. Section 6 summarizes the main conclusions of this study.

2. LOSSES REDUCTION METHODS

Several ways are available to alleviate losses in the distribution network (Al-Sarmi, S *et al.* 2019). However, some mechanisms require additional equipment to be installed in the system that can increase the financial burden for companies.

Several devices such as fluorescent lamps, distribution transformers at no-loads, induction motors with light or no loads in the distribution networks can lead to poor power factor in the system. Power factor improvement using capacitors is an effective method, which helps in reducing distribution system losses and maximizing the revenue. Power factor improvement can result in a reduction in the phase angle difference between the voltage and the current. The greater part of the loads in the distribution system is the inductive type, which needs reactive power to work. Installing a capacitor bank in parallel with the loads provides them with the necessary reactive power that lowers the phase angle difference between the voltage and current. Installing a capacitor bank can reduce the upstream current flow through the distribution lines, thus, reduces losses in the system. Another benefit of installing a capacitor bank is reducing voltage drop during heavy load periods. Such a capacitor bank installation requires determining the location of the capacitor bank placement, along with their types and proper sizes (Samineni S *et al.* 2010).

Switching optimization is also known as reconfiguration. It is a way of relocating the switching devices that already exist or introduce new devices in the appropriate location depending upon the size of loads, and the length and size of conductors. An effective method, switching optimization, helps in reducing technical losses in the distribution networks and improves its security. Compared to the method of reconductoring or new installation of feeders, switching optimization has been found as one of the most cost-effective methods to reduce the technical losses. Although the switching optimization method needs several new devices, the low-cost switching devices makes this method cost-effective compared to the reconductoring or new feeder installation method (Phetlamphanh V *et al.* 2012).

The selection of an appropriate conductor size can reduce the losses. The losses in the conductors depend on the connection quality at each end of the conductor, conductor size relative to the amount of current it carries, and the conductor operating voltage level. The line loss is inversely proportional to the conductor size and directly proportional to the square of the current that passes through the conductor. A smaller size of conductor can result in higher I2R losses and a higher voltage drop that causes a loss of credit for the DSO. The suggested practice is to ensure that the conductor is capable of delivering the peak demand of the consumers at the standard voltages. In other words, the voltage drop has to maintain within the standard range (Aburn G, and Hough M 2015). The shorter length distribution network can reduce distribution losses as studied in (Sadati SMB *et al.* 2012). Current density and heuristic index-based approximated optimal solution for conductor size selection for radial distribution system has been presented in (Wang Z. *et al.* 2000).

The main losses in distribution sub-stations are transformer losses. Two types of transformer losses: one is core (no-load) losses that are typically 25% to 30% of the total distribution losses and independent of the load (Al-Sarmi, S *et al.* 2019). This loss varies with the transformer size and the materials that are used to manufacture the transformer. The other one is the copper losses that mainly depends on the magnitude of current passes through the windings of the transformer, and it dissipates as heat. With the increase in loads, the material behaves like more resistive and hence increases line losses. For better management of distribution transformers, it is recommended to de-energize the transformer one or more times at low-load periods, which can help to reduce excessive core losses. Similarly, the distribution transformers need to switch them on at high-demand periods to reduce excessive copper losses. Furthermore, the DSO needs to identify customers having premises connected to oversized (or undersized) line transformers so that the DSO can optimize the transformers' sizes. An undersized transformer serving a particular load can operate with high losses.

The voltage upgrade is the changeover of lines and substations to the higher voltages. This method has developed practically to meet load growth or transmission requirements. It has several advantages in addition to the practical aspect; the economic advantages may be a benefit, especially if some of the used equipment can be used again with minimal modifications (Panek J, Elahi H 1989). This method plays a very important role in alleviating losses in case of the distribution network is overloaded. The best method in load balancing is to utilize the current duration curve, which can be developed for all three phases by the distribution system planner. Accordingly, if the loads in each phase of the distribution line are re-distributed, the losses can be minimized (Al-Sarmi, S *et al.* 2019). A tap-changing transformer allows adjusting the voltage level by altering turns the number of the transformer winding using a tap changer. In order to achieve a controllable voltage level, taps are normally adjusted on the high-tension side of the transformer. Off-load and On-load types of tap changing transformer are commonly utilized in the distribution network (Al-Sarmi, S *et al.* 2019).

With demand-side management, the DSO can reduce the overall system load, especially during peak periods, by turning off particular types of load or catering some stimulus for customers. Customer motivation to use smart and high efficient motors, refrigerators, and lighting systems can reduce the overall load (Al Badi AH *et al.* 2020). Advanced Metering Infrastructure (AMI) allows automated and bi-directional interaction between the smart utility meter with its IP address and the distribution company. The purpose of an AMI architecture is to update periodically about the real-time data related to power consumption to both the distribution companies and the consumers. It helps the customers to schedule their appliances to operate at the time of the best price and hence can reduce their cost of energy consumption (Al Badi AH *et al.* 2020).

3. RESEARCH METHODOLOGY

Some of the loss reduction methods unfolded in section 2 have been used in the MEDC network. Such methods are capacitor banks for power factor improvement, transformer size and location, and tap-changing transformers. Recently, the AMI method is currently under installation in the network. However, there is an opportunity to reduce the distribution network losses by selecting economic optimal conductors and cables and account for the cost of losses for the transformer load and no-load losses during the time of buying a new transformer.

The following subsections present the detailed models to calculate losses in a representative distribution network, models for calculating optimal conductor and cable selection, and models for determining no-load and load losses capitalization values of distribution transformers.

3.1 System Modelling and Losses Quantification

A load flow study is conducted to quantify the losses in a representative distribution network. The load flow model uses actual data for load, lines, transformers, and short circuit capacity, which are given by the MEDC. The load flow model solves the following power balance equations to determine voltages at the different buses, real and reactive power flows through the lines (Saadat H 2011).

$$P_k = \sum_{i=1}^{n} |V_k||V_i||Y_{ki}|\cos(\delta_k - \theta_{ki} - \delta_i) \quad (1)$$

$$Q_k = \sum_{i=1}^{n} |V_k||V_i||Y_{ki}|\sin(\delta_k - \theta_{ki} - \delta_i) \quad (2)$$

The non-linear power balance Eqns. (1) and (2) can be solved by different iterative methods such as the Newton-Raphson, the Gauss-Seidel, and the fast-decoupled methods. In this study, the Newton-Raphson method available in the ETAP software package is applied to solve the load flow equations. After solving the load flow problem, the system losses are computed by calculating the losses in any branch *k-i* using the following equations (Albadi M *et al.* 2017).

$$S_{loss,ki} = P_{loss,ki} + jQ_{loss,ki} = S_{ki} + S_{ik} \quad (3)$$

$$S_{ki} = V_k I_{ki}^* \quad \text{and} \quad S_{ik} = V_i I_{ik}^* \quad (4)$$

3.2 Optimal Cable and Conductor Selection

Increasing the cross-sectional area of the conductors/cables can reduce the energy losses in the cable; however, the large size conductors cannot be a choice for the DSO. This subsection presents a simple method of selecting the most economical conductor/cable sizes among the available sizes given by MEDC (Booth *et al.* 1988). The most economical conductor/cable size is determined by comparing the cost of losses for various conductors/cables with their extra construction/material cost considering peak load conditions.

The total peak power loss for three phases are calculated using the following equation,

$$P = 3I^2R \tag{5}$$

The annual demand cost per kW of peak losses is calculated as

$$C_{DC} = C_{WEC} \times N \tag{6}$$

The annual energy cost per kW of peak losses is calculated as

$$C_{EC} = C_{kwh} \times L_f \times H \tag{7}$$

L_f is the loss factor and can be determined as

$$L_f = \left(a \times LF\right) + \left(b \times LF\right) \tag{8}$$

where LF is the load factor, $a = 0.2$, and $b = 1 - a$. LF is defined as the ratio between the average load and the peak load for a given load pattern.

The total annual loss cost for per kW peak losses is determined as

$$C_{TAC/kW} = (C_{EC} + C_{DC}) \tag{9}$$

The total annual loss cost for total peak losses is determined using the following equation

$$C_{TAC} = (C_{EC} + C_{DC}) \times P \tag{10}$$

The cost of annual loss savings for a cable/conductor is calculated as

$$C_{AS} = (C_{TAC,PS} - C_{TAC,SS}) \tag{11}$$

The net annual savings for a cable/conductor is determined as

$$C_{Net,AS} = (C_{AS} - C_{ACC}) \tag{12}$$

The maximum net annual savings of a cable/conductor gives an indication about the most economical cable/conductor for a given annual peak load.

3.3 Capitalization of Losses for Distribution Transformers

The DSOs are always in the process of buying and installing distribution transformers because of the continuous expansion of the electrical distribution networks. Transformer economics is heavily connected to the pricing of the energy losses, e.g. load and no-load losses that occur during the transformer operation. The cost of such losses is important to calculate over the lifetime of the distribution transformers (Szwander W (1945)). The transformers with low initial cost may increase the cost of such losses over its lifetime, and vice versa. Therefore, the transformer-purchasing group needs to determine the cost of losses for the duration of the transformer lifespan in evaluating the most economical distribution transformer.

No-load losses capitalization value refers here as the value of one unit power loss in a distribution transformer under the no-load condition for the transformer lifetime. No-load losses capitalization value depends on the system capacity cost, and cost for generating, transmitting and distributing energy. No-load losses capitalization value is computed using the following equation (Al-Badi AH *et al.* 2011, Charalambous CA *et al.* 2013, and Wijayapala WDAS *et al.* 2016).

$$X = \left[\left(\frac{C_{SC} + HC_e}{1000\eta_T R_{fc} I_F}\right)\right] \tag{13}$$

Load losses capitalization value refers here as the value of one unit power losses in a distribution transformer under load condition for the transformer lifetime. The load pattern, growth of the load, and nature of the load profile are the main reasons for varying load losses capitalization value. Load losses capitalization value depends on the system capacity cost, the cost for generating, transmitting and distributing energy, yearly loss factor, peak responsibility factor, yearly peak load, and transformer fixed charge rate. Load losses capitalization value can be determined as (Al-Badi AH *et al.* 2011, Charalambous CA *et al.* 2013, and Wijayapala WDAS *et al.* 2016).

$$Y = \left[\left(\frac{C_{SC} R_F^2 + HC_e L_f}{1000\eta_T R_{fc} I_F}\right) \times P_{pl}^2\right] \tag{14}$$

The uniform annual peak load that can be determined based on IEEE loss evaluation guide as given in (C57.120-2017 Standard).

$$P_{pl} = \frac{LF}{\sqrt{L_f}} \quad (15)$$

The increasing factor is calculated as (Wijayapala WDAS *et al.* 2016)

$$I_F = \frac{\text{Purchase cost + Overhead + taxes}}{\text{Purchase cost}} \quad (16)$$

4. RESULTS AND DISCUSSION

4.1 System Modelling and Losses Quantification

This study model a selected 33 kV, 11 kV and LV network of a representative primary substation of MEDC network. The network consists of three 20MVA, 33/11kV transformers, 15 feeders and three 5MVar capacitor banks. Five feeders, namely FDR4, FDR5, FDR6, FDR7 and FDR8, are modelled in details up to the low voltage (415V) level. The components model such as transformers, lines, capacitors banks, loads and grid available in the ETAP software package are utilized to model the selected network.

The parameters such as kVA rating, impedance ratio, rated voltage for the transformers, type, length and cross-section for the cable, type and amount of load, short circuit capacity for the grid are obtained from the MEDC. Figure 1 shows the ETAP model for the selected 33 kV, 11 kV and LV network, while Figure 2 demonstrates the detailed model for one of the feeders FDR6.

The power flow problem is solved for the developed model at different load conditions. Such load conditions are maximum load, 80% of maximum load, 70% of maximum load, and minimum load. The load current drawn by each feeder in the developed model is comparable with the field-recorded load current for the corresponding feeder during peak load. The closeness of both current values verifies the accuracy of the developed model.

The load flow solution provides voltage profiles for each bus, line flows and losses occur in the network components. Figure 3 shows the voltage profile for the selected buses for different loading conditions. It reveals that voltages for all selected buses are within the recommended limit ($\pm 6\%$) except one bus Bus162FDR4, which has under-voltage at the maximum loading and 80% of the maximum loading. It also reveals that buses such as Bus R4/31 in FDR5 and Bus 167 in FDR7 maintain the minimum level of the required voltage during maximum loading.

The total kW and kVar losses for distribution networks at different load conditions are depicted in Figure 4. An increase in the load results in an increase in both the real power losses and reactive power requirements for the system. This result demonstrates that the system faces more losses during the peak demand, especially during the summertime.

Table 1 shows real and reactive power losses for different feeders. It is important to mention that real power losses are significant in the cables/lines because the current MEDC network has fatter cables than required. The use of the optimal size of the conductor can reduce these losses. The transformers also cause real power losses; however, the reactive power losses due to the transformer is significant as Table 1 revealed. These losses influence the transformer's total owning cost as the losses vary based on loading. Since the total owning cost has two major components such as the costs of load and no-load losses, therefore, the determination of capitalization values of losses at the time of buying a new transformer can reduce such losses during the transformer lifespan.

4.2 Optimal Cable and Conductor Selection for 11kV Networks

4.2.1 Economic Optimal Cable Selection

Table 2 shows a summary of the detailed calculation for economical cable selection based on peak load conditions—the study conducted for cable sizes, as mentioned in the first column of Table 2. The cable resistances are obtained from the datasheet found in the Oman cable website for 3C XPLE copper cable. The annual peak load for the cable is assumed to be 120 Ampere, which can be adjusted by the distribution company as they required.

The total annual loss cost for the total annual peak losses is calculated using Eqn. (10). The results are tabulated in Table 2. The total annual loss cost per kW peak loss is calculated using Eqns. (5)-(9). The results have been presented in Table 3.

The extra cost compared to the smallest size (70 sq.mm) of the cables is obtained from the MEDC. The annual carrying charge on extra construction cost is assumed to be 12% as found in (Booth *et al.* 1988). The cost of annual loss savings of each cable and the net annual savings for all cables have been obtained using Eqns. (11) and (12), respectively. All these calculated results are tabulated in Table 2.

Figure 5 shows the net annual savings versus the size of the cables. It reveals that 185 sq.mm is an optimal economic choice for carrying annual peak load current 120 Ampere and at a 0.5 load factor. It also indicates that the variation of the load factor, while keeping the peak load current constant, does not affect the cable size variation. In other words, the cable size remains the same as the optimal one; however, there a change in the amount of net annual savings is observed. On the other hand, it reveals that the optimal economic size of the cable can be changed if the peak load current is far from the expected peak load current.

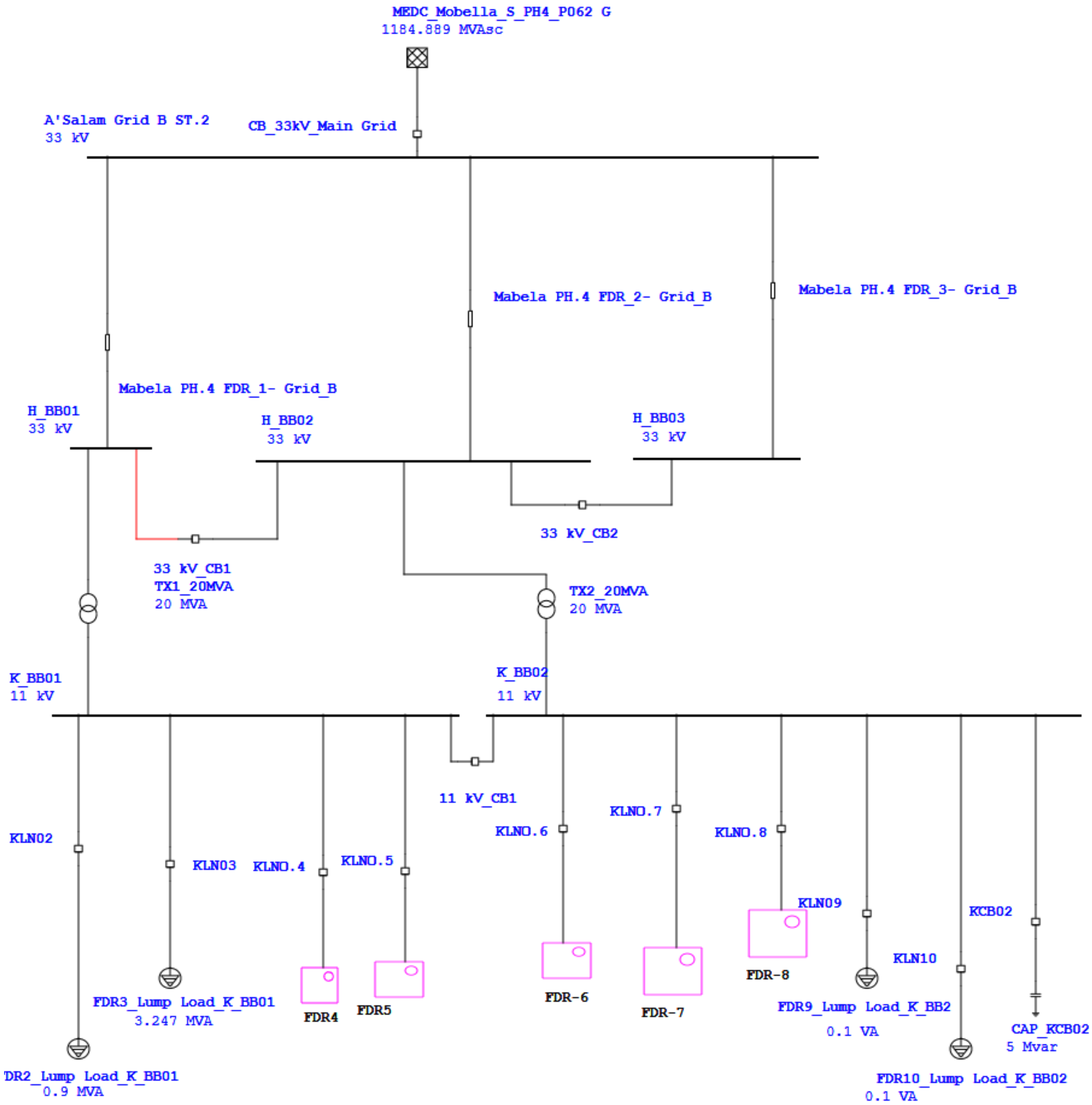

Figure 1. Components modelling in ETAP for the selected 33 kV, 11 kV and LV network.

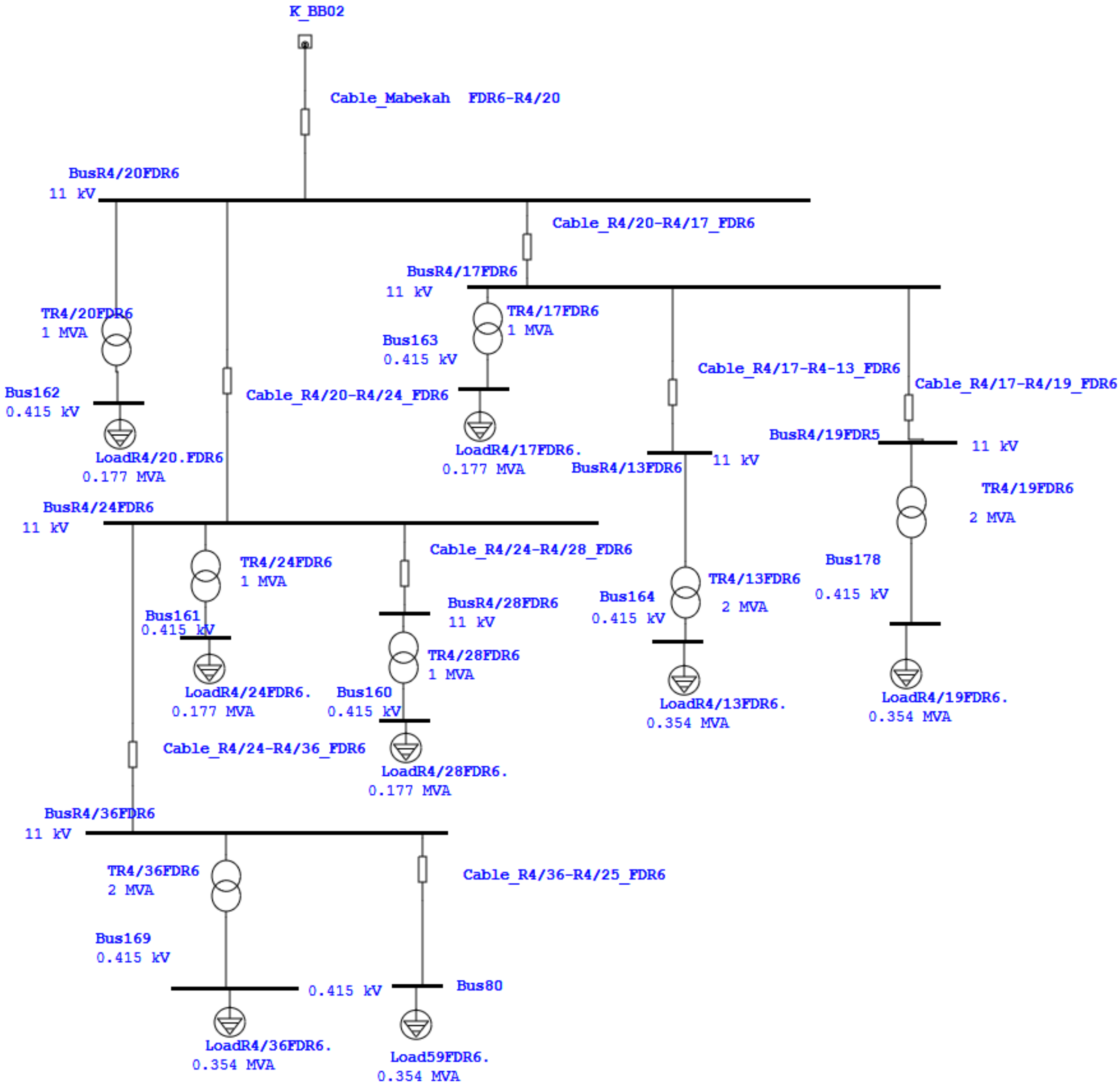

Figure 2. Feeder 6 (FDR6) detailed model that shows each low voltage (11kV/415V) distribution transformer and load.

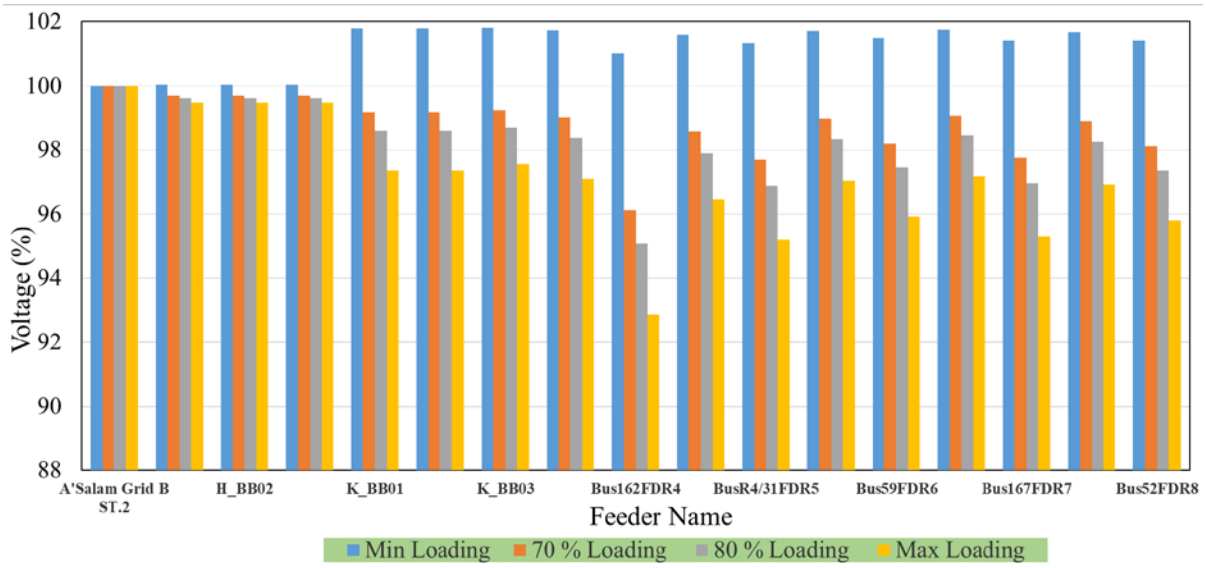

Figure. 3. Voltage profiles for the selected buses at different loading conditions.

Table 1. Real and reactive power loses in distribution transformers and cables for different feeders.

	kW losses (FDR	kVar losses (FDR4)	kW losses (FDR5)	kVar losses (FDR5)	kW losses (FDR6)	kVar losses (FDR6)	kW losses (FDR7)	kVar losses (FDR7)	kW losses (FDR8)	kVar losses (FDR8)
Cables/line	159.7	-28.3	81.8	-19.4	42.5	-60.8	81.8	-56.2	46.6	-39.6
Transformers	17.0	76.2	17.2	73.4	11.4	59.8	11.3	58.2	8.5	44.8
Total losses	176.8	47.9	99.2	53.9	53.9	1.0	93.1	2.1	55.5	5.2

Table 2. Cost of loss and net annual savings for various sizes of cables compared to the smallest size.

Cable sizes (sq. mm)	Cable resistance (Ohm/km)	Total peak loss for three phases (kW)	Total annual loss cost (OMR)	Extra construction costs in compared to the smallest size conductor (OMR)	Annual carrying charge on extra construction cost (OMR)	Annual loss savings compared to the smallest size conductor (OMR)	Net annual savings (OMR)
70	0.3420	14.77	3720.49	0.00	0.00	0.00	0.00
120	0.1960	8.47	2132.21	4100.00	492.00	1588.28	1096.28
150	0.1590	6.87	1729.70	6757.00	810.84	1990.79	1179.95
185	0.1280	5.53	1392.46	8698.00	1043.76	2328.03	1284.27
240	0.0982	4.24	1068.28	15099.00	1811.88	2652.21	840.33
300	0.0794	3.43	863.76	18300.00	2196.00	2856.73	660.73
400	0.0636	2.75	691.88	23100.00	2772.00	3028.61	256.61

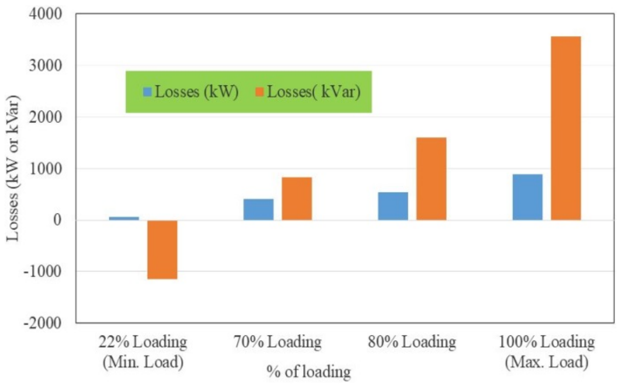

Figure. 4. Total losses (kW and kVar) in the distribution network for different loading conditions.

Table 3. Annual demand cost and energy cost detail.

Wholesale electricity purchase cost/kW-month (OMR)	17.7
Annual demand cost/kW (OMR)	212.4
Load factor	0.5
Loss factor	0.3
Cost/kWh (OMR)	0.015
Annual Energy cost/kW (OMR)	39.42
Total annual loss cost/kW(OMR)	251.8

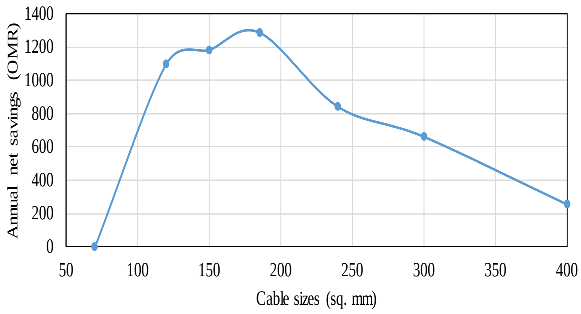

Figure. 5. Annual net savings variation for different sizes of cables for annual peak load current 120 A, 0.5 load factor, where the optimal size is 185 sq. mm.

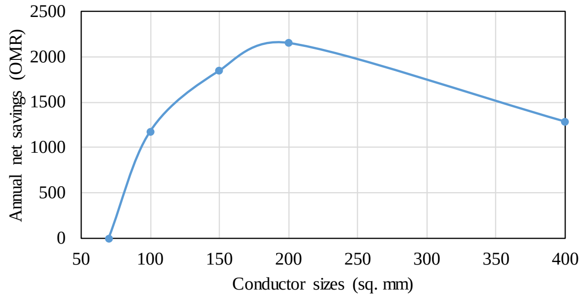

Figure. 6. Annual net savings variation for different sizes of overhead conductors for annual peak load current 120 A, 0.5 load factor, where the optimal conductor size is 200 sq. mm.

4.2.2 Economic Optimal Overhead Conductor Selection

The detailed calculation is carried out using Eqns. (5) – (12) as described for the economic optimal cable selection, and the detailed results are presented in Table 4. Table 4 shows a summary of the detailed calculation for economic optimal conductor selection based on peak load conditions. The study conducted for conductor sizes is mentioned in the first column of Table 4. The conductor resistances are obtained from the datasheet found in the Oman cable website for ACSR conductors. The annual peak load for the conductors is assumed to be 120 Amperes, which can be adjusted by the distribution company as they required. Figure 6 shows the net annual savings versus the size of the conductors. It is found that 200 sq.mm is an optimal economic choice for carrying annual peak load current 120 Ampere with a 0.5 load factor.

4.3 Capitalization of Losses for Distribution Transformers

4.3.1 Capitalization Value for No-load Loss

The capitalization value for no-load loss (*X*) is determined using Eqn. (13). Considering the distribution transformers as fixed assets (Wijayapala WDAS *et al.* 2016), the fixed charge rate is taken by combining the opportunity cost or minimum acceptable return as 12.75% and the book depreciation as 4%. Since there is no income tax in the country, thus it is taken as zero; however, local property tax and insurance is considered as 0.1 %. Thus, the fixed charge rate is found at 16.85%. Since the overall system loss for MEDC is 6.92%, thus the system efficiency is considered as 93.08%.

Equation 16 is used to calculate the increasing factor considering there is no overhead fee and taxes, and the factor is found 1. The system capacity is taken approximately as 40 OMR/kW/year as per (CRT 2017). The average cost of energy for the year 2018 is considered to calculate the levelized cost over the transformer lifetime (Capability Statement 2018). The discount rate and the inflation rate are considered as 7.5% and 6.425%, respectively. The cost recovery factor is utilized to calculate the annual levelized cost of energy. The levelized annual cost of energy is calculated as 0.0296 OMR/kWh. Thus, the no-load loss capitalization value was found 2.0467 OMR/W, as shown in Table 5. The calculated value in this study is higher than the value given in the Oman Electricity Standard (OES) as 0.8 OMR/W. Such a discrepancy may arise due to the differences in the load pattern, the system capacity cost, and the other parameters that were assumed in this study.

4.3.2 Load Loss Capitalization Value

The load loss capitalization value (Y) is determined using Eqn. (14). The loss factor is determined using the load factor of the transformer used in the distribution network. In order to determine the transformer load factor, it is essential to know the transformer load pattern even for a short period like one day during system peak load. With the use of the load profile of a distribution transformer, the load factor is determined by the ratio between the average load and the peak load. The load factor was calculated as 47.3% for a 2MVA transformer using the load profile provided by the MEDC. With this load factor, the loss factor was calculated as 0.2749. The peak responsibility factor was determined based on the IEEE loss guide (C57.120-2017) and was found as 0.9375.

The uniform annual peak load is calculated using Eqn. (15) as 0.9047. All calculated parameters are substituted to the Eqn. (14) to calculate the capitalization value of load loss, and it is found as 0.5959 OMR/W, as shown in Table 5. The calculated value in this study is higher than the value given in the OES (0.3 OMR/W). Such a discrepancy may arise due to the differences in the load pattern and transformer type (urban or rural), the system capacity cost, and the other parameters that are assumed in this study.

Table 4. Cost of loss and net annual savings for various sizes of conductors compared to the smallest size.

Conductor sizes (sq. mm)	Conductor resistance (Ohm/km)	Total peak loss for three phases (kW)	Total annual loss cost (OMR)	Extra construction costs in compared to the smallest size conductor (OMR)	Annual carrying charge on extra construction cost (OMR)	Annual loss savings compared to the smallest size conductor (OMR)	Net annual savings (OMR)
70	0.4156	17.95	4521.16	0.00	0.00	0.00	0.00
100	0.2885	12.46	3138.48	1681.70	201.80	1382.67	1180.87
150	0.193	8.34	2099.57	4737.10	568.45	2421.58	1853.13
200	0.1439	6.22	1565.43	6649.10	797.89	2955.72	2157.83
400	0.0712	3.08	774.56	20510.00	2461.20	3746.60	1285.40

Table 5. No-load and load loss capitalization values of a 2 MVA distribution transformer.

Capitalization Values	OMR/W
No-load loss	2.0467
Load loss	0.5959

5. CONCLUSION

Distribution companies consider the power loss in the distribution lines as a serious problem because of the energy and money wasted. This paper has presented different methods to minimize such losses. Distribution system losses cannot be phased out; however, it can be decreased by appropriate planning of systems to assure that power loss remain within an acceptable range. This paper reveals the following conclusion and recommendation for reducing losses in the distribution system and hence increasing the system efficiency:

- Losses in the distribution system can be quantified by modelling and simulating the network. Such a kind of study reveals the components or subsystems that contribute to higher losses in the system. Through modelling and simulation of a representative distribution network, it was found that transformers and cables/lines contribute higher losses among all other components in the system.
- Determining an economic optimal conductor/ cable from the available sizes by comparing the cost of losses for various conductors with their extra construction/material cost can reduce the losses in the cables/lines. The study is carried out based on peak load conditions instead of average load conditions because the losses change with the square of the current. It is shown that 185-sq.mm cable is an optimal economic choice for carrying an annual peak load current 120 Ampere with a load factor 0.5. At the same time, 200-sq.mm, an overhead conductor is found as an optimal economic choice for carrying annual peak load current 120 Ampere with a load factor 0.5.
- Capitalization values of the losses have a significant influence in evaluating the most economical distribution transformer. The utility can assess the capitalization value of the no-load and load losses using the measured load profile of various distribution transformers considering their lifetime. The utility can provide such values to the transformer manufacturing company and ask to design the requisition transformers accordingly. It was found in this paper that both the no-load and load loss capitalization values are higher than the values recommended by the Oman Electrical Standards (OES). Such differences may arise due to the differences in the variables such as the load pattern, load factor, transformer type (urban or rural), and the cost parameters, such as the system capacity cost, unit cost of energy, discount and inflation rates considered in the current study and the study done before. This study suggests recording the actual load profile of a particular distribution transformer for a period of time to determine its loss of capitalization values.
- Regular inspection and maintenance of distribution equipment such as isolators, connections, transformer and transformer bushings, LT switches and dropout fuses are required. Optimal location and appropriate size of the distribution transformers is an important factor. This study suggests placing the distribution transformers closer to the load centre and maintaining the minimum number of transformers, if possible.
- The feeders can directly supply heavy loads such as large buildings and industrial loads. Load balancing and appropriate load management can be considered for further reduction of the losses. The integration of digital, tamper-proof meters can help to reduce non-technical losses. In addition, the DSO can operate their system at a higher power factor. These suggestions can be further investigated for the network presented in this research.

CONFLICT OF INTEREST

The author declares no conflicts of interest.

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