Indonesian Journal of Electrical Engineering and Computer Science
Vol. 8, No. 2, November 2017, pp. 343 ~ 349
DOI: 10.11591/ijeecs.v8.i2.pp343-349

Energy Efficiency of a Building Using Capacitors Optimization

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Abstract

This paper presents the optimal location and sizing of capacitors to reduce the total power losses as well as its investment cost for a distribution system in a building. The capacitors location and sizing will be randomly chosen repetitively, via Stochasitic optimization method using MATLAB® and SIMULINK® software. The optimal capacitors location and sizing will be picked via analysis and comparisons between the results. The result shows improvement in power losses with minimal investment cost whilst providing optimal sizing and location of capacitors to be installed in a building.

***Keywords**: Stocastic optimization method, distribution system of a building, capacitor, power losses, minimum investment cost, energy efficiency.*

1. Introduction

With the steady economic growth in the world, energy demand has rose steadily, despite the fact that the main energy resources such as oil and gas are running low [1]. Hence, in the last decade, both the government and private sectors all over the world are trying to cut the dependency on fossil fuels, by optimising existing technologies to minimise the energy consumption, as well as venturing into renewable technologies [2]. Although only lately Malaysia is seen to be aggressively promoting renewable energy as a source of energy, it has already realized the need to diversify energy resources since the 1970s, during the world oil crisis, when it reveals the vulnerability of energy supply and demonstrated the world's overdependence on oil as a fuel [3]. This means that to sustain this increasing energy demand, while cutting the dependency on the fossil fuels, Malaysia needs to shift its energy generation to alternative energy resources or energy efficiency enhancement technologies [4, 5].

Capacitor installation indeed improves the voltage profiles and total power losses through cables or distribution line and proves to be a common method chosen among engineers to reduce power losses due to its low cost of investment, abundance availibility in the market as well as simple installation requirement [6]. When dealing with the distribution system containing several feeders and different loads, deciding the best locations and sizes of capacitors are becoming a complex optimization problem. The electric power supply delivers from the sources to the end users may cause a substantial energy loss. In conjunction to this agenda, implementation of current technology that is the capacitor optimal placement and sizing can be considered as a cost-effective approach towards reducing energy losses, hence improving the energy efficiency of an existing building [6]. However, the existing method of installation for bulk capacitor in a building system can be futher improvise by installing several capacitors with smaller sizes at varied riser’s location. In addition, this method can minimize the amount of capital investment needed to install capacitors without compromising the effectiveness of power losses reduction provide by the smaller capacitors installed at the selected risers. Hence, the issue of finding the optimal capacitors placement and sizing at risers can be solved by implementing the finest settings of capacitors performed by utilizing the proposed technique of

Received July 15, 2017; Revised September 30, 2017; Accepted October 14, 2017

optimal placement and sizing of capacitors via Stochastic Optimization approach. The main problem regarding capacitors placement and sizing is to minimize the total cost of energy losses per year embodied with the amount investment cost of capacitors whilst maintaining the power factor, voltage magnitude as well as total harmonic distortion within specified limit prescribed by the utility of Tenaga Nasional Berhad (TNB) and Energy Commission of Malaysia.

2. Research Method

The main problems that need to be solved in this paper involves with the importance of finding the solution for the power losses reduction without sacrificing system stability. This paper also emphasizes on the improvement of total cost spent for capacitors implementation by optimizing the size and location of capacitors in a distribution system of a building.

2.1. Problem Formulation Regarding Power Losses Improvement via Capacitors Implementation

The main purpose of installing capacitor banks in an electrical building system is to reduce the total power loss in a system. The formulation of total cost of power losses utilized in this study as the constraint for the Stochastic optimization (SO) method is given in equation **Error! Reference source not found.**.

$$P_{losses\_cost} = K_{en} \sum_{m=1}^{n} P_{losses_m} \tag{1}$$

where, m and n is the feeder number and total number of feeder, respectively, and K_{en} is the cost of energy.

In the market, the size of the capacitors is given in fixed size. In this study, a complete size of capacitors are designed based on the combination of several capacitors with the smallest size of Q_0^C.

Table 1. Discrete Capacitor Sizes Available in the Market Specified for the SSAAS Unbalanced Electrical Distribution System

Capacitor sizes (kVar)									
10	20	30	40	50	60	70	80	90	100
110	120	130	140	150	160	170	180	190	200
210	220	230	240	250	260	270	280	290	300

Capacitor installation cost is chosen proportional to the size of capacitor. The size of the capacitors to be installed at the selected destination is limited to the maximum size of reactive power load.

$$Q_{max}^C = L \times Q_0^C \tag{2}$$

where, Q_0^C is the smallest capacitor size shown in Table 1, and L is the multiple factor of the smallest size of capacitor to be installed. It is to be noted that the cost of capacitor may be varied on the market and is assumed to be at RM 60 per kVar based on average price for simplicity purposes.

2.2. Methodology

Stochastic optimization (SO) method working process is basically involved repetitive generation of random variables representing the electrical parameters indispensible for corroborating the formulation of objective function interdependencies to the system constraints. Initial selection of randomized parameters that falls under a specific range of constraints is performed as an incipient procedure to assist the futher optimization technique towards expediting the search of optimal location and sizing for capacitor. Without utilizing the proposed initialization procedure, this will cause an enormous number of capacitor sizing and location to be included in the proposed optimization technique.

The proposed SO methodology of randomly selected location for capacitors is implemented based on the repetitive process of randomly selected locations at risers for each transformer in a building distribution system. Once the process of SO is halted, comparison between the whole samples of randomly locations and sizing of capacitor is performed.

a) Perform a three-phase unbalanced load flow solution for the original system using SIMULINK® software in order to obtain the base case value of total active power losses, P_{total_loss}, using Equation (2).

$$P_{total\_loss} = \sum_{m=1}^{n} P_{loss_m} \quad (2)$$

where, *m* and *n* is the transformer number and total number of transformer, respectively.

The arrangement of P_{total_loss} of available risers will be in a matrix form of (*n*×3) for each transformer as illustrated in Equation (3).

$$P_{total\_loss\ r,\emptyset} = \begin{bmatrix} P_{total\_loss\ 1,a} & P_{total\_loss\ 1,b} & P_{total\_loss\ 1,c} \\ P_{total\_loss\ 2,a} & P_{total\_loss\ 2,b} & P_{total\_loss\ 2,c} \\ \vdots & \vdots & \vdots \\ P_{total\_loss\ r,a} & P_{total\_loss\ r,b} & P_{total\_loss\ r,c} \end{bmatrix} \quad (3)$$

where, $P_{total\_loss\ r,\emptyset}$ is the total real power loss at every phase, ∅, of a riser *r*.

b) Generate a matrix consisting of '1' and '0' as illustrated in equation (4) to represent the existences of phase current at a riser indicating whether the riser operation is available or not-available. Equation (5) is a numerical example for the $R_{r,\emptyset}$ with the value of ‘1’ that signifies it is suitable to install the capacitors since there is a current flowing through the phase of a riser which is connected with a load and vice-versa. Row of the matrix will indicate the riser number, while the column will indicate the phases of a distribution system in a building. In addition, Equation (5) can also be used to identify whether a particular riser is a three-phase riser or non-three-phase riser. The matrix is constructed for every transformer.

$$R_{r,\emptyset} = \begin{cases} 1, if\ I_{R_{r,\emptyset}} > 0 \\ 0, if\ I_{R_{r,\emptyset}} = 0 \end{cases} \quad (4)$$

where, $I_{R_{x,\emptyset}}$ represent the line current flowing through every phase, ∅, of a riser, x.

$$R_{r,\emptyset} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ \vdots & \vdots & \vdots \\ R_{r,a} & R_{r,b} & R_{r,c} \end{bmatrix} \quad (5)$$

where, ∅ is phase a, b or c, and *r* is the riser number, respectively.

c) Generate randomly a set of capacitors location at some of the available risers in a building distribution system using MATLAB® software. The randomly capacitors placement is selected among phases of risers which having the value of ‘1’ specified by $R_{r,\emptyset}$ given in equation (4). This indicates that it is suitable to install the capacitors since there is a current flowing through the particular phases of risers which are connected with the load and vice-versa. As a result, the matric $CAP_{r,\emptyset}$ given in equation (6) is attained consisting with the value of either ‘1’ or ‘0’ at the phase of a riser having $R_{r,\emptyset}$=1, to indicate selected and non-selected location for capacitors, respectively. However, selecting capacitors placement should also refer to the configuration of each riser whether it is a three-phase riser or non-three-phase riser. If any of the selected location is a three phase riser, then all of the columns in a row (row represents a three-phase riser) of $CAP_{r,\emptyset}$ will equal to '1' or '0'.

$$CAP_{r,\emptyset} = \begin{cases} [1\ 1\ 1]\ or\ [0\ 0\ 0], if\ R_{r,\emptyset} = [1\ 1\ 1] \\ 1\ or\ 0 \quad , if\ R_{r,\emptyset} = 1 \\ 0 \quad , if\ R_{r,\emptyset} = 0 \end{cases} \quad (6)$$

where, ∅ represent phase a,b or c and r represent riser number.

d) Use equation (11) to install a capacitor parallel with the load having less than 0.85 lagging power factor connected to a riser. By assuming that the capacitor did not draw any real power where P_{new} is equal to P_{base}. The desired power factor is 0.85 *p.f.* yielding to the angle of $\theta_{0.85p.f.} = cos^{-1}(0.85)$. Hence, a difference between the angles at base case condition (θ_{base}) and 0.85 *p.f.* ($\theta_{0.85p.f.}$) will divulges to an angle sustained by the capacitor, θ_{cap}, as given in equation **Error! Reference source not found.**.

$$\theta_{cap} = \theta_{base} - \theta_{0.85p.f.} \quad (7)$$

Equation **Error! Reference source not found.** can also be expressed as in equations **Error! Reference source not found.** and (9).

$$\tan(\theta_{cap}) = \tan(\theta_{base}) - \tan(\theta_{0.85p.f.}) \quad (8)$$

$$\tan(\theta_{cap}) = \tan(\theta_{base}) - \tan(\cos^{-1}(0.85p.f.)) \quad (9)$$

Equation (9) can be further derived as in equation (10).

$$\frac{Q_{cap}}{P_{new}} = \frac{Q_{base}}{P_{base}} - \tan(\cos^{-1}(0.85p.f.)) \quad (10)$$

Simultaneously, the size of a capacitor can be obtained by using equation (11)

$$Q_{cap} = P_{new} \times \left(\frac{Q_{base}}{P_{base}} - \tan(\cos^{-1}(0.85p.f.)) \right) \quad (11)$$

e) Calculate the total active power loss, P_{total_loss} by using equation (2) which will then used to calculate the total cost of power losses, P_{losses_cost} by using equation (1).
f) Repeat step (b) to (e) until the maximum iteration, h_{max} and save the best set of capacitors' location with respect to the minimum cost of total power loss.
g) Halt the repetitive process in the SO method during which the maximum iteration, h_{max} is reached. Record as well as analyze the obtained results and determine the best solution for capacitors placement and sizing with respect to the minimum cost of total power losses.

3. Results and Analysis

In this case study, an unbalanced distribution system of a building was considered as a test system for the analysis of optimal capacitors placement and sizing determined by using the proposed SO method. The electrical distribution system is operating in a nominal secondary voltage magnitude of 433 *V* where the voltage is stepped down by the five incoming transformers that fed from the utility substation operating at 11 *kV*. Each secondary side of incoming transformer is connected to the main switchboard (MSB) and from the MSB there are several risers wherein each riser is specifically connected to a respective load as shown in Table 2. There are several risers depending on the type of connected load described as below.

a) Motors/ Air Handling Units/ Split Unit Air-Conditioners (M).
b) Lighting and Power (N).
c) Emergency (E).
d) Fire alarm/ Sprinkler (P).
e) Lift (L).
f) Cooling Tower / Condenser / main A/C switchboard.
g) Others (O).

Table 2. Types Of Load Or Riser Connected To Every Incoming Transformer

Transformer	Types of Load or Riser						
Incoming Transformer 1 (T1)	M1	M2	N5	N2	M3	N1	-
Incoming Transformer 2 (T2)	O	E	O	N3	N4	-	-
Incoming Transformer 3 (T3)	M4	M5	MAIN A/C	E	N6	O	O
Incoming Transformer 4 (T4)	M6	M10	N8	M7	N7	-	-
Incoming Transformer 5 (T5)	M8	M9	M11	A/C	O	O	-

Extension and modification of the existing three-phase electrical distribution system such as the addition of split air conditioning units and extension of office space will also contribute to an intricate unbalanced loading condition of the system. The nominal or rated voltage magnitude of 415 *V* should be operated in the electrical distribution system of the building. However, it is contradictory with the existing voltage magnitude of 433 *V* pragmatically measured at all of the secondary side of the incoming transformer. As a result, a large voltage magnitude will cause to a higher energy consumption and vice-versa. The variation of voltage magnitude at the secondary side of incoming transformer as well as all the risers must obey the standard tolerance imposed by the Energy Commission, Malaysia. The latest tolerance is -6% to +10% for the nominal voltage magnitude of 400 *V* and this is different compared to the previous tolerance of -10% to +6% for the nominal voltage of 415 *V* [7].

3.1. Energy Efficiency Results for the Unbalanced Electrical Distribution System of a Building Determiend by using the Stochactic optimization Technique

Table 3 elucidates the results extracted from the base case condition of an unbalanced load flow solution performed on the electrical distribution system of a building during the peak loading condition. It is observed that the system draws a real and reactive power as much as 2950.01 *kW* and 1696.27 *kVar* for the consumption with the total real and reactive power losses of 4.86 *kW* and 2.47 *kVar*, respectively. In terms of percentage, the total real and reactive power losses incurred is not significant that is about 0.0476% and 0.0658% from the total real and reactive power drawn into the system, respectively. By assuming that the system operates at constant loading condition for 6 hours per day, 22 days in a month and 12 months in a year, the total cost of energy losses is RM 2,812.25 per year. The cost is calculated based on tariff (C1) given by the Tenaga Nasional Berhad (TNB) which is RM 0.365 per *kWh*.

Table 3. Results for The Base Case Unbalanced Load Flow Solution of An Electrical Distribution System in a Buildin

System parameters	Measured information
Total cost of energy losses (RM/year)	2,812.25
Total real power consumption (kW)	2950.01
Total reactive power consumption (kVar)	1696.27
Total real power loss (kW)	4.86
Total reactive power loss (kVar)	2.47
Total current flow through incoming feeder (kA)	5.219
Maximum voltage magnitude (V_{p-n})	253.44
Minimum voltages magnitude (V_{p-n})	250.12
Power factor (p.f.)	0.84
Maximum *THDv* (%)	3%

Based on Table 3, the maximum and minimum operating voltage magnitudes are 259.79 $V_{p\text{-}n}$ and 254.78 $V_{p\text{-}n}$, respectively. By referring to a new regulation prescribed by the Suruhanjaya Tenaga (ST), a new tolerance for the nominal voltage magnitude of 400 $V_{p\text{-}p}$ or 222 $V_{p\text{-}n}$ is within the range of 209 $V_{p\text{-}n}$ (-6%) and 254 $V_{p\text{-}n}$ (+10%). Thus, it is obvious that the maximum operating voltage magnitude of 259.79$V_{p\text{-}n}$ during the base condition does exceed the upper tolerance by 5 $V_{p\text{-}n}$. The power factor during base case condition is 0.844 *p.f*. which is lower than the minimum power factor of 0.85 *p.f.* This implies that the lower power factor is compelling the base system condition to draw excessive reactive power from grid. The total harmonic distortion of voltage magnitude (*THDv*) of 0.27% is obtained from the base case load flow solution which is slightly below the limit of 5%. Hence, it signifies that there is a small distortion of voltage magnitude signal causing to a small increase of temperature in the cables and electrical equipment.

Table 4 show the results of energy efficiency extracted from the unbalanced load flow solution of electrical distribution system in a building subject to the capacitors placement and sizing optimization performed by the SO method. The base case condition and h_{max}=10 repetitive processes in the SO method were performed on the unbalanced electrical distribution system during peak loading. It is observed that best solution for capacitors placement and sizing using the SO method appeared at the h=8th iteration have shown the system draws a real and reactive powers of 2955.67 *kW* and 1571.79 *kVar* for the consumption with the total real and reactive power losses of 4.07 *kW* and 1.85 *kVar*, respectively. This implies that the power consumption is increased by 0.19% or 5.66 *kW* compared to the base case condition. The value of power consumption increases mainly due to the slight increase in value of voltages throughout the incoming of a buliding as a result of capacitors installation. This problem signifies the needs to find another solution to maintain or reduce the incoming power to nullify the cost of energy consumption. Other than that, the optimal placement and sizing of capacitors using SO method provides a significant reduction of 16% and 25% for the total real and reactive power losses incurred in the system, respectively. By assuming that the system operates at constant loading condition for 6 hours per day, 22 days in a month and 12 months in a year, the total cost of energy losses is reduced to RM 2353.19 per year. This result indicates that the saving of RM 459.06 per year is obtained from the proposed approach as compared to the energy losses at base case condition with the total cost of RM 2,812.25 per year. Based on Table 4, the maximum and minimum operating voltage magnitudes are 253.44 $V_{p\text{-}n}$ and 250.47 $V_{p\text{-}n}$, respectively during the installed capacitors at optimal location and sizing. By referring to a new regulation prescribed by the Energy Commission of Malaysia, a new tolerance for the nominal voltage magnitude of 400 $V_{p\text{-}p}$ or 222 $V_{p\text{-}n}$ is within the range of 209 $V_{p\text{-}n}$ (-6%) and 254 $V_{p\text{-}n}$ (+10%). Thus, it is obvious that the operating voltage magnitude during the installed capacitors at the optimal location and sizing is comply with the tolerance prescribed by the Energy Commission of Malaysia. The power factor of 0.86 *p.f.* obtained corresponding to the implementation of the proposed method is a slightly improved that is above the minimum power factor of 0.85 *p.f.* and is complying with the standard imposed by the utility of Tenaga Nasional Berhad (TNB). The total harmonic distortion of voltage magnitude (*THDv*) of 3% is improved and is below the *THDv* standard limit of 5%.

Table 4. Results Comparison between Base Case and OCPS with Stochastic approach.

System parameters	Base case	8th iteration of SO method
Total cost (RM)	RM 2,812.25	RM 6,903.25
Total cost of energy losses (RM/year)	RM 2,812.25	RM 2,353.19
Total cost of capacitors (RM)	-	RM 4,550.06
Total real power consumption (kW)	2950.01	2955.67
Total reactive power consumption (kVar)	1696.27	1571.79
Total real power loss (kW)	4.86	4.07
Total reactive power loss (kVar)	2.47	1.85
Total current flow through incoming feeder (kA)	5.219	5.103
Total capacitors size (kVar)	-	70
Maximum voltage magnitude ($V_{p\text{-}n}$)	253.44	253.44
Minimum voltages magnitude ($V_{p\text{-}n}$)	250.12	250.47
Average power factor (p.f.)	0.84	0.86
Maximum *THDv* (%)	3%	3%

Figure 5 depicts the highest capacitor size of 10 *kVar* is located at several optimal locations of load mainly consisting with the motors, air handling units and split air-conditioner units in the building. It is noteworthy to notify that there is no capacitor implemented at the Incoming Transformer 2 (T2) due to the fact that the base case power factor is already reached to the minimum requirement of 0.85 *p.f.* specified by the TNB. The compendium of results signify that the mere implementation of capacitors location and sizing is not sufficient to significantly improve the energy efficiency for all electrical parameters of the unbalanced system in a building. Hence, the need to provide another solution to significantly improve the energy efficiency mainly on the energy consumption is still need to be addressed.

Table 5. Optimal Location and Sizing of Capacitors for the Unbalanced Electrical Distribution System Prescribed via Stochastic Optimization Method

Incoming Transformer 1 (T1)	Risers Name	M1	M2	N5	N2	M3	N1	-
	Cap size (kVar)	-	10	-	-	-	-	-
Incoming Transformer 2 (T2)	Risers Name	O	E	O	N3	N4	-	-
	Cap size (kVar)	-	-	-	-	-	-	-
Incoming Transformer 3 (T3)	Risers Name	M4	M5	MAIN A/C	E	N6	O	O
	Cap size (kVar)	10	-	10	-	-	-	-
Incoming Transformer 4 (T4)	Risers Name	M6	M10	N8	M7	N7	-	-
	Cap size (kVar)	-	10	10	10	-	-	-
Incoming Transformer 5 (T5)	Risers Name	M8	M9	M11	A/C	O	O	-
	Cap size (kVar)	-	-	10	-	-	-	-
Total Capacitor Size (kVar)				70				

4. Conclusion

This paper has presented the Stochastic Algorithm Technique that is used to solve the problem of optimal capacitors placement and sizing on a building. The results have shown that the optimal capacitors placement and sizing improves the energy effiency performance of the unbalanced electrical distribution system in terms total real power losses with minimum cost of installation whilst satisfying all of the system constrainst such as the limitations of THDv, voltage magnitude and power factor.

Acknowledgment

The authors would like to acknowledge The Institute of Research Management & Innovation (IRMI), UiTM, Shah Alam, selangor, Malaysia for financial support of this research. This research is supported by IRMI under the LESTARI Grant Scheme with project code: 600-IRMI/MyRA 5/3/LESTARI (0024/2016).

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