Optimal Location and Size of Capacitor Banks in Distribution Network with Harmonic Distortion

Nikola Krstić

Abstract – **Growing presence of nonlinear loads in distribution networks leads to deterioration in the quality of operation of these networks due to injection of higher harmonics. In this paper, optimal location and size of capacitor banks (CB) in distribution network with the presence of higher harmonics, for different priority factors, are determined, in order to see the efficiency and suitability of this, often used solution for reactive power compensation, in the presence of harmonic distortion. Metaheuristic particle swarm optimization (PSO) method was used to find optimal solution to the optimization problem. IEEE18 distribution network was used as a test network, and computer simulations, for results generation and verification, were done in the Matlab software.**

Key words – **capacitor banks; particle swarm optimization; harmonics; distribution network.**

I. Introduction

Regardless of the type of nonlinear load that is the source of harmonic distortion, their negative effect is reflected in the reduction of distribution network capacity, increased heating, interference with communication lines and general decrease of quality of electric energy, which badly affects the operation of connected loads. All these phenomena that occur due to harmonic distortion somewhat change the operation of distribution network and require a revaluation of previous traditional solutions used for network operation improvement. Specifically, in this paper, the influence of CB for reactive power compensation, on distribution network operation with the presence of higher harmonics is observed [1-2]. Connection of CB to the distribution network enables the compensation of consumers reactive power, which results in the reduction of reactive power taken from the network. This leads to a reduction in power losses and voltage drops, which is of great importance especially in distribution networks, where as a rule, they are the largest. In addition to reducing energy losses [3] and voltage deviations from the reference [4], the paper also considers reducing the total harmonic distortion of voltage (THDV) [4] in distribution network with CB connection. Precisely these quantities, in addition to the costs that are proportional to the rated power of connected CB, with certain weight coefficients will make up the multi-parameter criterion function of the optimization problem. Although locations and powers of CB are fixed, they must be optimal taking into account all load conditions that can occur in observed distribution network. For this reason, whole load diagram which represents the load power that usually occur in observed network, is used in simulations, and not some of its part. Also, one source of higher harmonics will be used, a nonlinear load connected in 5th node of the observed network.

In this paper, four different solutions to the optimization problem will be presented, in relation to the chosen priority of sizes in criterion function. To solve the optimization problem of optimal location and power of CB, PSO metaheuristic optimization method [5] will be used. The influence of higher harmonics will be analyzed by decoupled method in the frequency domain [6], where interdependence of different harmonics is not taken into account, but a separate network model is made for each frequency (harmonic). Steady state for fundamental harmonic, will be determined by backward/forward sweep algorithm [7], for the calculation of power flows in radial distribution networks. Z-bus matrix and current injection vector for higher harmonics will be used to determine higher harmonic node voltages [6]. In order to see the influence of load type on the operation of network in these conditions, two different load types will be considered [3]. First is the constant impedance and the second the constant power load type.

II. Optimization Problem Definition

Optimal location and size of CB, is a nonlinear optimization problem with constraints. Control variables in this optimization problem are the locations of CB in the network (network nodes) and their rated powers. Constraints of the control variables are given by (1) and (2).

$$Q_{cn} = k \cdot Q_{cn_{min}},\ \ k \in N \tag{1}$$

Where are: Q_{cn} –rated reactive power of connected CB, $Q_{cn_{min}}$ – rated reactive power of the smallest unit used.

$$i \in \{i_1, i_2, \dots i_n\} \tag{2}$$

Where are: i - index of network node in which CB is connected, $\{i_1, i_2, \dots i_n\}$- set of network node indexes in which is possible to connect CB.

In this optimization problem, dependent variables are node voltages, currents in network branches and THDV in every node. Constraints of these variables are given by (3), (4) and (5).

$$U_{min} < U < U_{max} \tag{3}$$

U is the network node voltage.

$$I_g < I_{gmax} \tag{4}$$

I_g is the network branch current.

N. Krstić is with the Department of Power Engineering, Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: nikola.krstic@elfak.ni.ac.rs

$$THDV < THDV_{max} \quad (5)$$

THDV is the total harmonic distortion of voltage.

As the values of the dependent quantities can't be known in advance, there is a chance that the constraints applied to them will not be met in the initial iterations, so there must be a mechanism in optimization method which will reject this type of solutions. In the paper, penalty function is used for this purpose. Beside the constraints in the form of inequality, there are also constraints in the form of equality, which applied to power balance equations and determine the steady state. These constraints are expressed with (6) and (7):

$$P_G = P_L + P_{loss} \quad (6)$$

Where are: P_G- generated active power (comes from the network source node), P_L- active power consumed (used by all loads), P_{loss} – losses of active power in the network.

$$Q_G = Q_L + Q_{loss} \quad (7)$$

Where are: Q_G- generated reactive power (comes from the network and CB), Q_L- reactive power consumed by loads, Q_{loss}- losses of reactive power in the network.
Unlike the active power flow, which in passive distribution networks always has a direction from the source node (network) to consumers, the direction of reactive power flow, in this case may be different, depending on the compensation level of connected CB.
In addition to the constraints, in defining the optimization problem, it is necessary to determine the criterion function, whose minimization should be performed. In this case, a multi-parameter criterion function will be used, because connecting CB it is desired to achieve a general improvement of the distribution network operation in the presence of harmonic distortion. This is achieved by minimizing multiple variables, including energy losses, cost of CB, deviation of the voltage from the referent value and THDV of all network nodes. Variable load power in observed period of time will in certain extent change the voltage in network nodes and therefore the THDV, during this period. Because of this, criterion function will consider maximum sum of voltage deviation and maximum sum of THDV that appear in network nodes in observed time period. Criterion function is given by (8).

$$F = a_1 \cdot \sum_k (P_{loss,k} \cdot \Delta t) + a_2 \cdot \sum_i Q_{cni} + a_3 \cdot \sum_i (U_i - \\ -U_{ref})^2 + a_4 \cdot \sum_i THDV_i \quad (8)$$

Where are: F – criterion function that needs to be minimized, $P_{loss,k}$- power losses in the distribution network in k-th time interval, Q_{cni} – rated reactive power of CB connected in i-th node, U_i – voltage of i-th node in time interval with maximum sum of voltage deviation, $THDV_i$ – THDV of i-th node in time interval with maximum sum of THDV in network nodes, a_1, a_2, a_3, a_4 –weight coefficients.
Power losses, in some time interval, due to the existence of higher harmonics, are determined from (9).

$$P_{Loss} = 3 \cdot \sum_{i,j} (\sum_h I_{gij}^{(h)2} \cdot real\{Z_{gij}^{(h)}\}) \quad (9)$$

Where are: $real\{Z_{gij}^{(h)}\}$ - real part of the branch impedance between i-th i j-th node for h-th harmonic, $I_{gij}^{(h)}$- current of the h-th harmonic in the branch between i-th i j-th node.
THDV for i-th node is given by (10).

$$THDV_i(\%) = \frac{\sqrt{\sum_{h>1} V_{ih}^2}}{V_{i1}} \cdot 100\% \quad (10)$$

Where are: $THDV_i$ – THDV of i-th node, V_{i1}-fundamental harmonic of voltage in i-th node, V_{ih}- h-th harmonic of voltage in i-th node.

III. SOLVING THE OPTIMIZATION PROBLEM

Metaheuristic method of PSO is used to find the optimal solution to above defined optimization problem. Values of the steady state are determined by backward/forward sweep method, for the calculation of power flows in the network, for the fundamental harmonic, and using the Z-bus matrix and vector of injected currents for higher harmonics.

A. Particle Swarm Optimization Method

Particle swarm optimization (PSO) is one of the population metaheuristic optimization methods, and is inspired by the process of flock of birds finding food in nature. The population consists of a set of individuals, each represent a potential solution to the optimization problem and a set of control variables that need to be adjusted. Individuals in the population communicate with each other and move towards the individual that is in place with the largest amount of food and thereby minimum value of the criterion function. In order to perform a better search of the solution space, the direction of movement of an individual is affected not only by the location with the largest amount of food found so far (g_{best}), but also by the location with the largest amount of food that individual has found so far (p_{best}). In this way, each subsequent generation of individuals in the population will be closer to a larger food source and thus closer to the optimal solution. Specified optimization method can be analytically expressed with (11) and (12).

$$v_i(t+1) = w \cdot v_i(t) + C_1 \cdot r_1 \cdot (p_{besti}(t) - x_i(t)) + \\ +C_2 \cdot r_2 \cdot (g_{best}(t) - x_i(t)) \quad (11)$$

$$x_i(t+1) = x_i(t) + v(t+1) \quad (12)$$

Where are: t – ordinal number of iteration (generation), x_i– location of i-th individual, v_i- speed of i-th individual, w – inertia coefficient, C_1, C_2- acceleration coefficients, r_1, r_2- random numbers from interval $[0,1]$.

B. Considering Higher Harmonics

Steady state analysis for higher harmonics was done using matrix equation given by (13), taking into account, Z-bus matrix, which is found as inverse Y-bus matrix, and vector of injected currents for higher harmonics.

$$\boldsymbol{V_h} = [Y_h]^{-1} \cdot \boldsymbol{I_h} = [Z_h] \cdot \boldsymbol{I_h} \tag{13}$$

Where are: $\boldsymbol{V_h}$ –node voltage vector for h-th harmonic, $\boldsymbol{I_h}$- current injection vector for h-th harmonic, $[Y_h]$ − Y-bus matrix for h-th harmonic, $[Z_h]$ − Z-bus matrix for h-th harmonic.
As there is only one nonlinear load connected in node 5, thus only one coordinate in vector of injected currents of higher harmonics is different from zero, and is given by (14).

$$I_{h5} = \frac{S_5}{\sqrt{3}U_5} \cdot \frac{1}{h} \tag{14}$$

Where are: h - harmonic order, I_{h5}- current of h-th harmonic injected in node 5, U_5- voltage of 5^{th} node, S_{p5}- apparent power of the nonlinear load.
It is clear that by changing the frequency (order of harmonic), Y-bus matrix also changes, because the reactance, susceptance, and to a certain, small extent, the resistance in the network change. Takin into account the skin effect, resistance of medium voltage network built of overhead lines, changes with the change of order of harmonics according to (15) [8].

$$R^{(h)} = R^{(1)} \cdot (0.9996 + \frac{0.07345 \cdot h^2}{192 + 0.05878 \cdot h^2}) \tag{15}$$

Where are: $R^{(h)}$- branch resistance for h-th harmonic, $R^{(1)}$- branch resistance for fundamental harmonic, h- order of harmonic.
Dependency of reactance and susceptance in the network from the order of harmonic is given by (16) and (17).

$$X_L^{(h)} = h \cdot X_L^{(1)} \tag{16}$$
$$B_C^{(h)} = h \cdot B_C^{(1)} \tag{17}$$

Where are: h - order of harmonic, $X_L^{(h)}$- reactance for h-th harmonic, $X_L^{(1)}$- reactance for fundamental harmonic, $B_C^{(h)}$- susceptance for h-th harmonic, $B_C^{(1)}$- susceptance for fundamental harmonic.
Equations (16) and (17) will, in addition to describing the elements of distribution network, be used to model reactance and susceptance for constant impedance loads, for higher harmonics. Modeling constant power loads for higher harmonics due to their more complex nature requires a slightly different approach. Constant power loads are usually industry loads, with electric machines that have rotating parts in them. Equivalent impedance of this type of load usually depends on the ratio of the speed of rotation of the machine and the circular frequency of the source. As higher harmonics have a significantly higher circular frequency than the fundamental harmonic, which determines the speed of rotation of the machine, it can be stated that the impedance for fundamental harmonic for constant power load type is approximately the same for all higher harmonics and correspond to the stiff rotor impedance. Reactance of the constant power loads for higher harmonics is also obtained from (16), while the resistance is the same as that for fundamental harmonic. Impedance for fundamental harmonic, for this type of load, is calculated from (18), whose obtaining process is explained in the appendix.

$$Z_1 = 0.1 \cdot Re\{Z_p\} + j0.3 \cdot Im\{Z_p\} \tag{18}$$

Where are: Z_1 −fundamental harmonic impedance for constant power load, Z_p − fictive impedance for constant power load, calculated from (19).

$$Z_p = \frac{U_n^2}{S_p^*} \tag{19}$$

Where are: U_n −rated network voltage, S_p^* −conjugated complex power of constant power load.

IV. Simulation Parameters and Results

In order to check the efficiency and verification of the proposed optimization method in finding the optimal solution for the mentioned optimization problem, computer simulations were performed in the Matlab software package. Standard IEEE18 distribution network with nonlinear load, shown in the Fig. 1, was used as the test network.

A. Simulation Parameters

Transformation ratio of the transformer is fixed and is set to 35/10 kV/kV for all observed cases. Referent voltage has a value of $U_{ref} = U_n = 10$ kV, while the maximum and minimum allowed voltage is 10 % higher and lower than the referent one. For the maximum value of THDV in one of the network nodes, the value of 5% was taken, and the maximum allowed current per network branch on 10kV side is set to 125A (current slightly higher than the maximum current in the network for rated load). Also, rated power of CB is an integer product of rated power of the smallest unit, for which a value of 25 kVAr was used. Apparent power of nonlinear load is 0.45 MVA. In this paper, odd harmonics up to 25^{th} are taken into account.

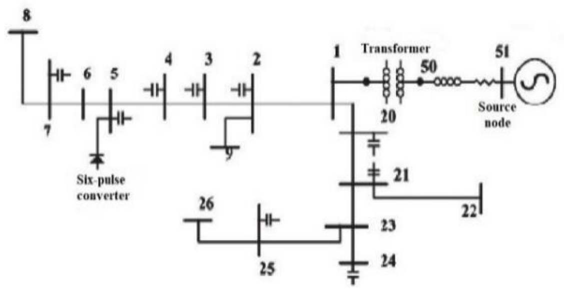

Fig. 1. IEEE18 distribution network with nonlinear load

Paper considers two types of load, both with the same load power for 10 kV voltage which load diagram is shown in Fig.2.

Time dependence of active and reactive load power of each node is the same, and follows the time dependence given by the load diagram, for both types of load, with a value of 1MVAr for reactive power peak.

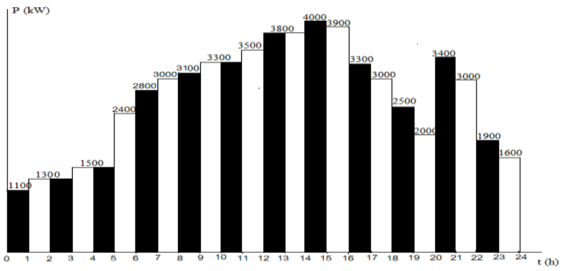

Fig. 2. Load diagram

Values of the acceleration coefficients in the PSO, are C_1=0.5 and C_2=0.9, while the coefficient of inertia is 1. Optimization method was performed over a population of 70 individuals, and to solve the optimization problem, in every case, 100 iterations were performed.

In solving the optimization problem, each individual in the population is described with 32 characteristics. First 16 refer to the indexes of nodes in which CB are connected, and the other 16 to their rated powers. Optimization method is realized so that it is possible to connect more CB in the same node, while their rated powers can be equal to zero. In this way, the number of nodes in which CB are connected is not predetermined, but is indirectly determined in the process of execution of optimization method, which increases the possibility of finding a global solution to the problem. Taking into account all 10kV network nodes increases processing time, but for this relatively small test network it is the best way to find optimal solution, especially in this case where multi-parameter criterion function is consider.

Values for weight coefficients in criterion function are determined based on the desired priority, using 0.05 $/kWh for the first one. Thus, equal priority of all sizes is achieved if all members of the criterion function have approximately the same value, and a higher priority of a certain size, in this paper, is taken into account by increasing its member about ten times compared to others. As the goal of this paper is not to consider the economic aspects and exact costs, but to observe the change of the main aspects of network operation after CB connection, in the case of different priorities, the exact values of weight coefficients and criterion function are not important and so are not presented.

B. Simulation Results and Analysis

Table I sows the representative sizes of criterion function in distribution network before CB connection, with rated transformation ratio of the transformer, for constant impedance and constant power load type, respectively.

TABLE I
REPRESENTATIVE SIZES OF CRITERION FUNCTION IN DISTRIBUTION NETWORK BEFORE CB CONNECTION

Load	Z load type	S load type
W_{loss} (MWh)	4.271	6.107
$\Sigma(Ui-Ur)^2$ $(kV)^2$	14.015	22.614
$\Sigma THDV_i$ (%)	47.689	38.003

From Table I it can be seen that better network performances in terms of voltage profile and energy losses are obtained for constant impedance load. This is due to an increase in load currents in the case of reducing the voltage, for constant power load type and the opposite for constant impedance load. However, constant power load has lower THDV due to the lower values in Z-bus matrix compared to those for constant impedance load.

Obtained results after connecting CB on distribution network are shown in Tables II and III. Table II contains the CB location in the network (node index) and their rated powers. Table III contains values of representative sizes of criterion function, which determined the network operation with CB connected. Four different cases of criterion function depending on the desired priority were considered. In the second case, the highest priority is given to the reduction of energy losses, in third to the minimization of voltage deviations, the fourth greatest importance gives to the reduction of THDV, while in the first one all aspects in criterion function have the same priority.

TABLE II
OPTIMAL LOCATIONS AND RATED POWERS OF CB

Priority	All equal		W_{loss}	
Load	Z type	S type	Z type	S type
node	1	1	1	1
Qc(kVAr)	150	200	125	225
node	3	2	4	3
Qc(kVAr)	50	50	100	100
node	4	3	6	5
Qc(kVAr)	25	175	350	250
node	7	7	8	6
Qc(kVAr)	675	300	75	150
node	8	8	20	7
Qc(kVAr)	225	225	125	175
node	9	21	21	8
Qc(kVAr)	50	100	150	75
node	22	22	23	20
Qc(kVAr)	125	125	50	175
node	/	25	24	23
Qc(kVAr)	/	25	125	125
node	/	26	/	25
Qc(kVAr)	/	75	/	75
Priority	$\Sigma(U_i-U_r)^2$		$\Sigma THDV_i$	
Load	Z type	S type	Z type	S type
node	2	2	1	6
Qc(kVAr)	200	175	25	50
node	4	3	7	7
Qc(kVAr)	50	375	925	750
node	5	7	8	8
Qc(kVAr)	125	125	250	500
node	7	8	20	9
Qc(kVAr)	650	675	50	50
node	8	9	21	20
Qc(kVAr)	125	150	50	200

node	9	20	22	21
Qc(kVAr)	200	425	300	100
node	20	22	23	22
Qc(kVAr)	125	125	100	150
node	22	23	/	25
Qc(kVAr)	125	500	/	100
node	23	25	/	/
Qc(kVAr)	200	175	/	/
node	24	/	/	/
Qc(kVAr)	125	/	/	/
node	26	/	/	/
Qc(kVAr)	425	/	/	/

TABLE III
VALUES OF REPRESENTATIVE SIZES OF CRITERION FUNCTION

Priority	All equal		W_{loss}	
Load	Z type	S type	Z type	S type
W_{loss} (MWh)	5.228	5.692	4.416	5.667
ΣQ_C (kVAr)	1300	1275	1100	1350
$\Sigma(Ui-Ur)^2$ $(kV)^2$	7.077	11.974	8.165	11.593
$\Sigma THDV_i$ (%)	38.826	41.460	59.519	45.728
Priority	$\Sigma(U_i-U_r)^2$		$\Sigma THDV_i$	
Load	Z type	S type	Z type	S type
W_{loss} (MWh)	6.808	7.932	6.057	7.313
ΣQ_C (kVAr)	2350	2725	1700	1900
$\Sigma(Ui-Ur)^2$ $(kV)^2$	3.039	3.528	5.200	7.334
$\Sigma THDV_i$ (%)	35.059	28.296	30.531	23.995

From the results shown in Tables II and III it can be concluded that connection of CB on distribution 10 kV network can reduce voltage deviations by 78.31% and 84.39%, and THDV by 35.97% and 36.86%, for constant impedance and constant power load type respectively, compared with the case with no CB connection. Great improvement of voltage profile is partly a result of very low voltage in the network in time of highest load before CB connection, and its further improvement is prevented by a current constraint in network branches, which became dominant due to the connection of a large amount of reactive power to the distribution network. Similar situation is in the case of reducing THDV where current constraint does not allow the connection of CB with even greater rated powers in some nodes, which would further reduce the elements in the Z-bus matrix and thus voltage harmonics. Also, energy losses reduction of 7.2% for constant power load is significant, considering the fact that reactive power of consumption is four times smaller than the active power. Connection of CB inject reactive power in the network which increases node voltages, therefore energy losses in the case of constant impedance load increase because of dominant active power dependency. This fact resulted in the optimization method not being able to reduce energy losses for this type of load, while meeting all the set constraints, (mainly voltage constraints).
Largest rated power of CB connected in a single node, mostly that is the node close to the source of harmonics and the end of the network (node 7), is in the case where THDV reduction had the highest priority. Locations and rated powers of connected CB, in the case of energy losses reduction, are such that compensate the reactive power of the load but also set the voltage in define limits, which is the reason for somewhat higher total rated power of connected CB than total reactive power of load (1MVA). Improvement of the network voltage profile is achieved by connecting CB of medium size in a large number of nodes, for fine voltage adjustment. In this case total rated power of connected CB is the largest, due to poor voltage profile before CB connection in time of peak load. When all aspects of criterion function have the same priority, optimization method managed to achieve an improvement of two of the three sizes in the criterion function, with total rated power of CB similar to those in the case of energy losses reduction.
Fig. 3 shows the voltage (base voltage is 10kV) and Fig. 4 shows the THDV in all network nodes before and after CB connection, for both types of load, in the time of highest power consumption (14-15h) as the most critical period.

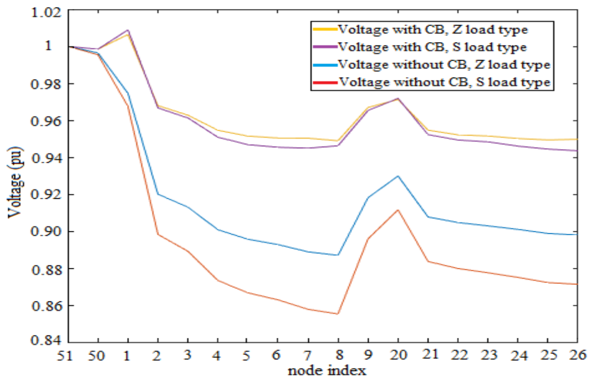

Fig. 3. Network node voltages with and without CB, for both load types

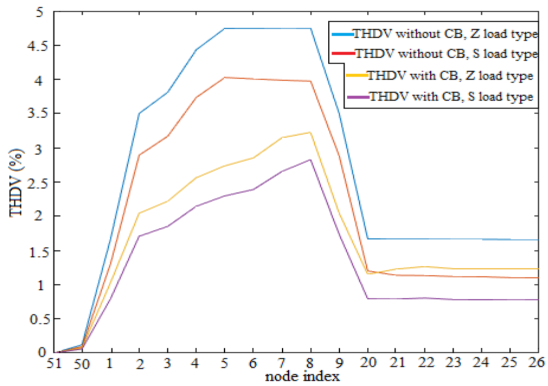

Fig. 4. Network node THDV with and without CB, for both load types

Like Table III, Figs, 3 and 4 also show that with adequate connection of CB, voltage profile and THDV in distribution network with harmonic distortion can be greatly improved.

V. CONCLUSION

In this paper, the optimization problem of optimal location and size of CB, in standard IEEE18 distribution network with a nonlinear load, using metaheuristic optimization method of PSO is successfully solved. Results of the optimization problem showed that connection of CB in distribution network with the presence of harmonic distortion, can improve operation of this network especially in terms of improving voltage profile and reducing THDV. Also, reduction of energy losses is much greater if distribution network has a higher share of constant power load type and lower power factor. However, it must be noted that improvement of all three observed network aspects in the same time is very hard to achieve using only CB.

APPENDIX

Equation (18) which determines the impedance of constant power load for the fundamental harmonic, is obtained respecting the ratio of impedance in nominal operation mode and impedance of the stiff rotor mode. Here, the assumption is made, that the constant power load consists of industrial drives composed mostly of induction motors. Equivalent impedances of the induction motor for the nominal and the stiff rotor operating mode were calculated based on the simplified equivalent scheme for steady state of induction motor, shown on Fig. 5.

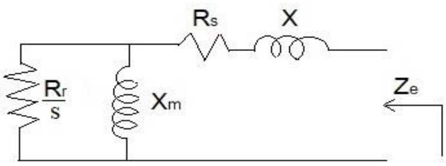

Fig. 5. Simplified equivalent scheme of induction motor

Based on the equivalent scheme, after rationalization, equivalent impedance is:

$$Z_e = R_s + \frac{R_r}{s} \cdot \frac{X_m^2}{X_m^2 + (R_r/s)^2} + j\left(X + X_m \cdot \frac{(R_r/s)^2}{X_m^2 + (R_r/s)^2}\right) \qquad (20)$$

In order to obtain a concrete value for the ratio of these two impedances, appropriate and realistic assumptions related to the motor parameters and its operation were adopted. In particular, it is accepted that in the nominal operating mode, equivalent resistance is three times higher than the equivalent reactance, taking into account the ratio between active and reactive power used in the constant power loads. It is also accepted that rotor and stator resistances are equal ($R_r = R_s$) and twice less than the sum of rotor and stator reactance ($X = 2R_r$), while slip coefficient s in nominal operating mode is $s_n = 0.05$. Considering the proposed assumptions and using (20), equivalent impedance of the motor in nominal and stiff rotor operating mode is obtained from (21) and (22), respectively.

$$Z_{e,N} = (19.867 + j6.623) \cdot R_r \qquad (21)$$

$$Z_{e,K} = (1.999 + j2.012) \cdot R_r \qquad (22)$$

Ratio between impedance in stiff rotor (21) and nominal operating mode (22) is the same as the ratio between the impedance for fundamental harmonic and the fictive impedance, given in (18).

REFERENCES

[1] L. Du, L. He, R. G. Harley, “A survey of methods for placing shunt capacitors banks in power network with harmonic distortion”, IECON 2012 – 38th Annual Conference on IEEE Industrial Electronics Society, pp. 1198-1203, October 2012.
[2] A. Mujezinović, N. Turković, N. Dautbašić, M. Muftić Dedović, I. Turković, “Use of Integer Genetic Algorithm for Optimal Allocation and Sizing of the Shunt Capacitor Banks in the Radial Distribution Networks”, 18th Internatiomal Symposium INFOTEH-JAHORINA, pp. 58-64, 20-22 March 2019.
[3] J. Vuletić, M. Todorovski, “Reduction of Losses and Harmonic Distortion in Distribution Networks with Different Load Models by Placing Shunt Capacitors using Integer Genetic Algorithm”, Przeglad Elektrotechniczny, vol. 1, no. 6, pp. 86-89, June 2015.
[4] M. Milovanović, J. Radosavljević, B. Perović, “Određivanje optimalnih lokacija i snaga kondenzatorskih baterija u distributivnim mrežama u cilju smanjenja harmonika i poboljšanja naponskog profila primenom genetskog algoritma”, Tehnika, vol. 72, no. 6, pp. 867-875, January 2017.
[5] J. Radosavljević, *Metaheuristic Optimization in Power Engineering*, London, United Kingdom, Institution of Engineering and Technology, 2018, pp. 75-113.
[6] M. Milovanović, J. Radosavljević, B. Perović, M. Dragičević, “Proračun tokova snaga u distributivnim mrežama u prisustvu viših harmonika”, 17th Internatiomal Symposium INFOTEH-JAHORINA, pp. 127-131, 21-23 March 2018.
[7] J. A. Michline, S. Ganesh, “Power Flow Analysis for Radial Distribution System Using Backward/Forward Sweep Method”, World Academy of Science, Engineering and Technology; International Journal of Electrical and Computer Engineering vol. 8, no.10, pp. 1628-1632, 2014.
[8] D. Tasić, *Osnovi elektroenergetske kablovske tehnike*, Niš, Serbia, Electronic Faculty of Niš, 2001, pp. 59-67.