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Automatic network capacitive balancing technique for resonant grounded power distribution systems

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Md Abdul Barik[1,2] ✉, Ameen Gargoom[1], Md Apel Mahmud[1], Md Enamul Haque[1], Martin Cavanagh[3], Hassan Al-Khalidi[4], Aman Maung Than Oo[1]

[1]*Centre for Smart Power and Energy Research (CSPER), School of Engineering, Deakin University, Geelong, Australia*
[2]*REFCL Program Engineering, AusNet Services, Melbourne, Australia*
[3]*Operational & Access Planning, AusNet Services, Melbourne, Australia*
[4]*Asset Maintenance & Support, AusNet Services, Melbourne, Australia*
✉ *E-mail: mbarik@deakin.edu.au*

Abstract: This study presents an automatic network balancing technique to limit the capacitive unbalance in resonant grounded power distribution systems (RGPDSs). The aim of this capacitive balancing technique is to minimise the unbalance current through the line to ground (which is the current through the neutral of the system) in order to automatically limit the neutral voltage. The proposed technique is designed by combining the weighted-sum technique and genetic algorithm (GA), where distributed switched capacitor banks (SCBs) are used for balancing RGPDSs. The proposed technique is employed to optimise available SCBs for limiting the network unbalance at the substation under a pre-defined threshold considering all possible network configurations. The unbalances at different locations of the network are also minimised to limit the system unbalance within the threshold due to minor changes in network parameters. Since the lifetime of capacitor banks relies on the switching, the proposed technique is designed in such a way that the system balance is achieved with the minimum switching. The performance of the proposed technique is evaluated through simulation studies in *MATLAB/SimpowerSystems* environment. Simulation results show that the proposed technique works well and capable to maintain the capacitive balance of the system with changes in network configurations.

1 Introduction

Faults in electrical power systems have severe consequences and the powerline bushfire is considered as one of the most destructive natural disasters, which is a consequence of such faults [1]. Among the faults in power systems, single phase-to-ground faults are the most common and liable for the powerline bushfire [1, 2]. The chances of powerline bushfires from electrical faults depend on energy delivered to the fault, which is proportional to the fault current. Hence, it is essential to limit the fault current. Resonant grounding (RG) approach is used to limit the fault currents for mitigating powerline bushfires [3].

In a resonant grounded power distribution system (RGPDS), the neutral of the distribution transformer is grounded through an arc suppression coil (ASC). The ASC needs to be perfectly tuned with the zero-sequence impedance of the system in order to mitigate bushfires due to electric faults while such tuning is not important in other applications of the RG. However, the neutral voltage of RGPDSs will be higher in a healthy condition if the shunt capacitors are unbalanced [4]. This high neutral voltage is not acceptable it may cause safety hazards (e.g. electrocution) and furthermore, the neutral voltage displacement is usually used to detect ground faults in RGPDSs [5, 6]. Therefore, the sensitivity of the fault detection will depend on the unbalances in shunt capacitances, as the fault detection algorithms are faster than network balancing algorithms. Thus, it is essential to manage the system capacitive unbalance within a limit for safety issues as well as to maintain the sensitivity of the fault detection in RGPDSs.

In a RGPDS, the capacitive unbalance of the system can be limited using additional capacitor banks. One option is to use a capacitor bank for each automatic switchable section (i.e. a small part of the network), where each capacitor bank will be responsible to balance a specific section and ultimately, the entire system will be balanced. The limitation of this approach is that it requires one capacitor bank for each individual section, which is not a cost-effective solution.

Another alternative way to balance the system is to use a limited number of capacitor banks distributed throughout the system. In this case, the required total size of capacitors will be smaller than the case, where capacitor banks are placed in all sections. The location and size of the capacitor banks are required to be selected based on the unbalance of all sections, feeders and the substation (i. e. the entire system). In the case of network capacitive balancing using a limited number of capacitor banks, it is required to optimise the settings of capacitor banks for balancing the entire system including all feeders and sections, which have capacitor banks. If capacitors banks are not properly optimised, some sections may have small unbalances while the amount of unbalances may be higher for other sections, which will result in a higher overall network unbalance for the entire system. Therefore, optimal use of capacitor banks is important for different parts of the network and this has to be done automatically for balancing the entire system.

The main objective of the proposed algorithm in this paper is to optimise the settings of available capacitor banks for limiting the network capacitive unbalance at the substation under a specified threshold. However, the capacitive unbalance at the substation will change with changes in network configurations (e.g. connections or disconnections of sections or feeders to or from the system). Therefore, the settings of capacitor banks need to be adjusted in such a way that the network unbalances at the substation will be within the pre-defined threshold for all possible network configurations. The overall network unbalance, i.e. the unbalance at the substation is also affected with changes in unbalances in different feeders and sections within the network. Therefore, the unbalances at feeders and sections also need to be minimised so that the overall network unbalance does not cross the threshold with small changes in different feeders and sections. Moreover, it is very common in power industries to use SCBs in order to balance the capacitive unbalance and for this case, the search space is discrete in nature. Such optimisation problems can be defined as

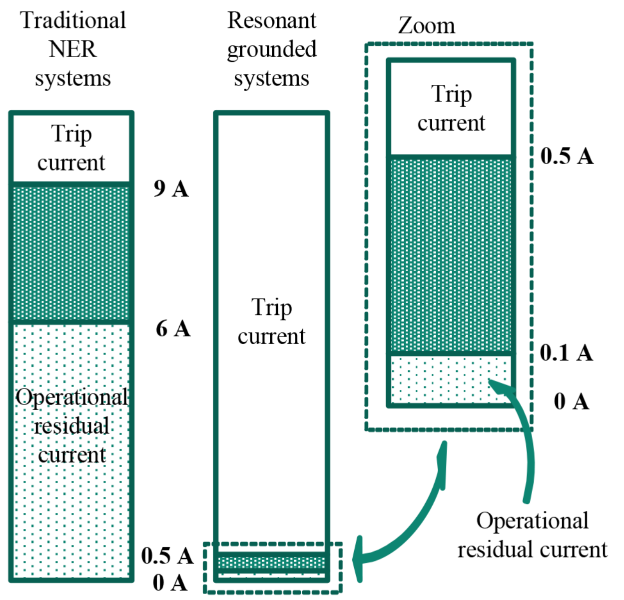

Fig. 1 *Sensitivity requirements to detect ground faults and the operational ranges of the neutral current for both resistive and resonant grounded systems*

multi-objective problem with integer variable and non-linear constraint [7].

The existing literature does not cover automatic network balancing techniques using capacitors, particularly for RGPDSs, as the RG approach is fairly new and uncommon for mitigating powerline bushfires. There are some well-known optimisation techniques available in the literature, such as Pareto-based [8, 9], decomposition-based [10, 11] and branch and bound [12]. Pareto-based optimisations, such as non-dominated sorting genetic algorithm (NSGA)-II and multiobjective evolutionary algorithm based on decomposition (MOEA/D) are designed for continuous variable while decision variables are integer in the given problem. Moreover, Pareto search-based algorithms are not suitable for the automatic balancing algorithm, as it requires a single solution instead of Pareto-front. Moreover, the branch and bound optimisation techniques are designed for the single objective optimisation problem, where the given problem is a multi-objective optimisation problem.

In power systems, capacitor banks are optimally used for different applications, such as power loss minimisation, reactive power compensation and voltage profile improvement [13]. For this purpose, a scheme based on the particle swarm optimisation (PSO) is used in [14, 15] to determine optimal capacitors, which method does not work for the scattered problems [16]. Fuzzy-based approaches are used in [17, 18] to find out the optimal size of capacitor banks, which offer good solutions for mixed-integer problems but these approaches are unable to handle many rules at a time. A mixed-integer linear programming model is used in [19], which provides a good solution to find the size and location of capacitor banks. However, this is not suitable for the non-linear optimisation problem.

The most commonly used optimisation technique for selecting the optimal size and location of the capacitor banks is genetic algorithm (GA) [7, 20, 21], which is capable to find the global optimal solution over various functions [16]. GA has the ability to handle both continuous and discrete parameters for both linear and non-linear problems [16]. Moreover, existing literature [22, 23] on optimisation in power system indicates that GA works better than other mathematical optimisation algorithms, where constraints are highly non-linear and the decision variables are integer. However, the simple GA usually does not provide good solutions for multi-objective problems (especially, for the problems with three or more objectives) [24]. In this case, the weighted-sum technique, as presented in [24, 25] can be used to convert multi-objective to a single objective, as this allows users to select weight factors for different objectives based on the priority requirement within the system.

The combination of the GA and weighted-sum approach is used in [4] for balancing RGPDSs. In [4], the settings of capacitor banks are optimised in order to limit unbalances in the substation, feeders and sections under the threshold. This has been done by considering only the present network configuration. However, the connections or disconnections of feeders or sections are very common during the practical operation of power distribution systems and the network balancing technique in [4] does not guarantee that the unbalance at the substation will be under the threshold for all possible network configurations. Moreover, the settings of all capacitor banks are frequently changed in [4] in order to balance the system even for a very small change in the network unbalance. The frequent switching of capacitor banks reduces the lifetime. Another major shortcoming of the balancing technique in [4] is that the balancing technique considers that the capacitor banks are variable, which can be varied to any value within a range. However, it is most common that the capacitor banks are switched in nature with fixed set-points.

An improved network capacitive balancing technique is presented in this paper in order to overcome the above shortcomings. Though the combination of the GA and weighted-sum method is used in this paper, the proposed scheme estimates the unbalance at the substation for all possible network configurations and the settings of the capacitor banks are then optimised to limit capacitive unbalances at the substation under a pre-defined threshold. Moreover, the unbalance at all individual feeders and sections are considered based on their priorities while optimising the settings of capacitor banks to balance the system. These priorities are defined based on the operational characteristics of the network. In this paper, the network balancing at the substation is set to the highest priority and the same of different sections is set as the lowest priority while the unbalance at the feeder is prioritised between the substation and sections. For all cases, the optimisation problems are formulated by considering switched capacitors while ensuring the minimum switching of these capacitors. Finally, all these activities are framed in the form of an algorithm to balance the system automatically. This automatic balancing algorithm can be embedded in the supervisory control and data acquisition (SCADA) system, which will collect the measurements of unbalances from the field devices and find out the optimised setting for capacitor banks and balance the system if necessary. In addition to this algorithm, another algorithm is used in this paper for field devices, which helps to reduce the cost of communication to collect data from such devices.

2 Significance of capacitive balancing in resonant grounded systems

In RGPDSs, the residual current will flow through the ASC (i.e. neutral-to-ground) if shunt capacitances of the distribution lines are unbalanced. As a result, a voltage will be induced at the neutral point of the transformer, which needs to be limited to ensure safety and maintain the sensitivity requirements for the fault detection devices.

The requirements of the fault detection sensitivity are different in traditional neutral earth resistor (NER) grounded systems and RGPDSs with having a target of mitigating bushfire from powerline-to-ground faults. Fig. 1 shows the sensitivity requirements to detect ground faults and the operational ranges of the neutral current for both the NER grounded systems and RGPDSs. From this figure, it is seen that the trip currents are different for NER grounded systems and RGPDSs. The trip currents are ∼9 A for NER grounded systems (it may vary system to system around 9 A), where it is 0.5 A for RGPDSs to minimise the chances of bushfire from powerline-to-ground faults [1, 26]. As the trip currents are high for NER grounded system, the allowable neutral current (i.e. allowable unbalance) is also high, which is ∼6 A after a margin of 3 A. However, the allowable range for the unbalance current (i.e. neutral current) is very small in RGPDSs, which is ∼100 mA after having a margin of 400 mA. Therefore, maintaining the network capacitive unbalance under 100 mA (or

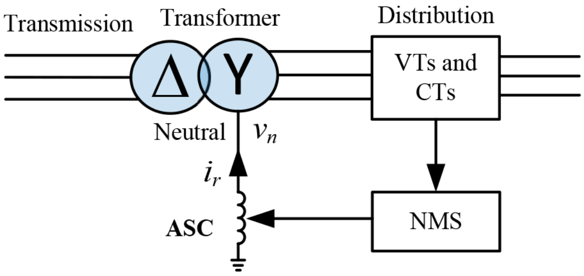

Fig. 2 *Distribution substation with the resonant grounding, where NMS stands for neutral management system*

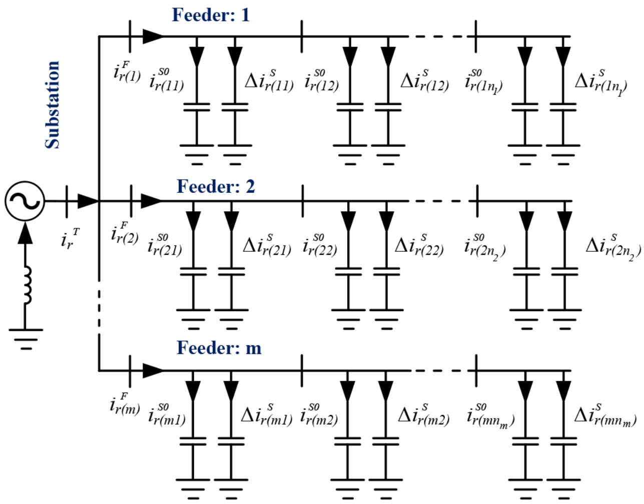

Fig. 3 *One-line diagram of a simple power distribution system representing the residual current flow (all capacitors are the three-phase capacitors and load currents are ignored for the simplicity)*

the allowable unbalance limit based on the system requirement) is necessary to ensure the sensitivity of the fault detection in RGPDSs and mitigating bushfire from powerline-to-ground faults.

Moreover, the effect of the unbalances on the neutral voltage are different in NER grounded systems and RGPDSs. In the NER grounded systems, the neutral voltage is directly proportional to the neutral current (i.e. unbalanced current). However, this relationship is not applicable for the RGPDSs, where the neutral voltage is much higher in RGPDSs comparing to the NER grounded system, as the inductance at the neutral of the system makes resonant condition with the network's shunt capacitances. For example, an unbalance of 1% can increase the neutral voltage ∼4 kV [4], where it is also depends on the damping of the system.

3 System modelling

The substation of a simple RGPDS is shown in Fig. 2 from where it can be seen that an ASC is connected between the neutral point of the distribution transformer and ground. Therefore, the neutral voltage will be high if the current flowing through the neutral of the system (which is also known as residual current or unbalanced current) is high. The relation between the neutral voltage ($v_{\rm n}$) and the residual current ($i_{\rm r}$) can be expressed as

$$v_{\rm n} = -i_{\rm r} z_{\rm ASC} \tag{1}$$

where $z_{\rm ASC}$ is the impedance of the ASC. From (1), it is clear that the neutral voltage is directly proportional to the residual current. Therefore, it is essential to limit the residual current to ensure the neutral voltage within the acceptable limit. As the loads in RGPDSs are usually not connected to ground, the residual current is a result of the unbalances in shunt capacitors of lines in different phases. Therefore, the residual current can be expressed as

$$i_{\rm r} = I_{ag} + \alpha^2 I_{bg} + \alpha I_{cg} \tag{2}$$

where I_{abcg} are the equivalent currents corresponding to shunt capacitors in different phases and $\alpha = 1\angle 120°$. From (2), it can be seen that the residual current will be zero if I_{abcg} are balanced (i.e. $I_{ag} = I_{bg} = I_{cg}$). If the shunt capacitors are not balanced, a residual current will flow, which will induce a neutral voltage. To minimise the residual current, additional capacitors can be added and (2) can be modified as follows:

$$\begin{aligned} i_{\rm r} &= (I_{ag}^0 + \Delta I_{ag}) + \alpha^2 (I_{bg}^0 + \Delta I_{bg}) + \alpha (I_{cg}^0 + \Delta I_{cg}) \\ \text{or,} \quad i_{\rm r} &= i_{\rm r}^0 + \Delta i_{\rm r} \end{aligned} \tag{3}$$

where $i_{\rm r}^0$ and I_{abcg}^0 are the existing residual current and line-to-ground currents through shunt capacitors in different phases, respectively; $\Delta i_{\rm r}$ and ΔI_{abcg} are the residual current and line-to-ground currents in different phases corresponds to the added capacitor, respectively.

Equation (3) is the general equation for the residual current with the added capacitor bank. However, a power distribution system consists of several feeders and each feeder consists of several sections, as shown in Fig. 3. The equations for the residual current at different locations of the network can be derived from Fig. 3. Using (3), the residual current ($i_{{\rm r}(ij)}^{\rm S}$) of section ij (section j of feeder i) can be written as

$$i_{{\rm r}(ij)}^{\rm S} = i_{{\rm r}(ij)}^{\rm S0} + \Delta i_{{\rm r}(ij)}^{\rm S} \tag{4}$$

where $i_{{\rm r}(ij)}^{\rm S0}$ and $\Delta i_{{\rm r}(ij)}^{\rm S}$ are the existing and the added shunt capacitors (current equivalent) for section ij, respectively. From Fig. 3, it can be seen that the residual current of a feeder ($i_{\rm r}^{\rm F}$) is the summation (vector summation) of the residual current through all sections of the respective feeder, which can be represented as

$$i_{{\rm r}(i)}^{\rm F} = \sum_{j=1}^{n_i} i_{{\rm r}(ij)}^{\rm S} \tag{5}$$

where n_i is the number of sections in the $i^{\rm th}$ feeder. Similarly, the total residual current at the substation ($i_{\rm r}^{\rm T}$) is the summation (vector summation) of the residual current of all sections in the entire system, which can be expressed as

$$i_{\rm r}^{\rm T} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} i_{{\rm r}(ij)}^{\rm S} \tag{6}$$

where m is the number of feeders in the system. Equation (6) represents the residual current at the substation in the current network configuration. However, the residual current at the substation will be different for different network configurations and it can be represented as

$$i_{{\rm r}(k)}^{\rm T} = \sum_{ij \in U_{s(k)}} i_{{\rm r}(ij)}^{\rm S} \quad \text{for } k = 1, 2, 3, \ldots, K \tag{7}$$

where $i_{{\rm r}(k)}^{\rm T}$ is the residual current at the substation for a specific network configuration k, $U_{s(k)}$ is the set of sections connected to the system in the respective network configuration k and K is the number of possible network configurations.

In this paper, changes in network configurations are considered if any switchable section (one or more) is connected or disconnected to/from the network. The extension (or modifying) of a line inside a section will change the unbalance of the respective section, but it is not considered as a change in the network configuration rather than a change in the unbalance for a section. The proposed network capacitive balancing technique based on this system modelling is presented in the following section.

4 Network capacitive balancing technique

The different objectives and derivation of the final objective of this problem are presented in the following subsections.

4.1 Objectives

As discussed earlier, the first objective of this research is to limit the absolute value of the residual current under a specified threshold for different parts of the network by optimising available capacitor banks. This objective is treated as a constraint, which is discussed in Section 5. The second objective is to further minimise the residual currents in which it does not cross the threshold with minor changes in the network unbalance. The objective functions for the substation, feeders and sections, respectively, are

$$\min_{\Delta I_{abcg}^{S}} [I_{r(k)}^{T} = \text{abs}(i_{r(k)}^{T})] \quad \text{for } k = 1, 2, 3, \dots, K \tag{8}$$

$$\min_{\Delta I_{abcg}^{S}} [I_{r(i)}^{F} = \text{abs}(i_{r(i)}^{F})] \quad \text{for } i = 1, 2, 3, \dots, m \tag{9}$$

$$\min_{\Delta I_{abcg}^{S}} [I_{r(ij)}^{S} = \text{abs}(i_{r(ij)}^{S})] \quad \text{for } ij \in U_{sc} \tag{10}$$

where I_r^T, I_r^F and I_r^S are the absolute values of the residual currents at the substation, feeder and section level, respectively; and U_{sc} is the set of sections with capacitor bank. Thus, the objectives of this optimisation problem are presented in (8)–(10), which can be considered as a multi-objectives optimisation problem, where some objectives have priorities over others. The proposed technique to balance the network considering the priorities of minimising residual currents at different locations of the network is discussed in the following subsection.

4.2 Squeezing multi-objectives to a single objective

In the proposed technique, the multi-objective problem is converted to a single objective one using the weighted-sum method [24] by considering their priorities. For this purpose, all objectives need to be multiplied by their respective weight factor and sum-up them to get the final objective. The objectives presented in (8)–(10) is converted to a single objective using the weighted-sum method as

$$\min_{\Delta I_{abcg}^{S}} \left[\sum_{k=1}^{K} W_{T(k)} I_{r(k)}^{T} + \sum_{i=1}^{m} W_{F(i)} I_{r(i)}^{F} + \sum_{ij \in U_{sc}} W_{S(ij)} I_{r(ij)}^{S} \right] \tag{11}$$

with $\sum W_{T(k)} + \sum W_{F(i)} + \sum_{ij \in U_{sc}} W_{S(ij)} = 1$ where W_T, W_F and W_S are the weight factors for the substation, feeder and section level, respectively. The weight factors in (11) are required to be set based on the priority requirement of the system. In this work, it is considered that priorities for all feeders are the same and similarly, it is the same for all sections. However, priorities for the network configuration, where all sections are connected (usual network configuration), are double than the other network configurations as this configuration is the most desirable one.

Moreover, it is considered that the priority at the substation is higher than the feeders (i.e. $W_{T(k)} > W_{F(i)}$) as the neutral voltage of the system directly depends on the residual current at the substation. Similarly, it is considered that priorities at the feeders are higher than sections (i.e. $W_{F(i)} > W_{S(ij)}$). In general, the priorities can be defined as

$$W_T = \beta_1 W_F = \beta_2 W_S \tag{12}$$

with $\beta_2 > \beta_1 > 0$ where β_1 and β_2 are the priority indexes. In this paper, substations are priorities double than the feeders and feeders are priorities double than the sections, i.e. $\beta_1 = 2$ and $\beta_2 = 4$. It is worth to mention here that these priorities are used to find the optimised solution from feasible candidate solutions. However, the priority indices need to be selected based on the priority of the given network and industry requirement, where the selection criteria of the priority indices are out of the scope of this paper.

To summarise, (11) represents the combined objective function to minimise the network capacitive unbalance, i.e. the residual current. The candidate solutions to reduce the amount of unbalances by using the available capacitor banks, are obtained by a practical strategy in which the system balance is achieved with minimum switching of capacitor banks. The detailed strategy is discussed in Section 6. The adopted strategy based proposed technique is incorporated into balance the system using the GA (GA toolbox in MATLAB) by considering boundary conditions and constraints as presented in the following section.

The developed technique in this section is capable of balancing the shunt impedance of the network to increase the fault detection sensitivity in RGPDSs. However, the system voltage can change with varying the phase-to-ground capacitive reactances during the network balancing. As the capacitor banks for balancing the system are connected between phases-to-ground, the phase-to-ground voltages will be impacted during the network balancing. Again, the neutral-to-ground voltage will mainly be affected by changing the capacitance for balancing the network as the phase-to-neutral voltages are maintained at the substation using an auto tap changer. However, the main target of the network balancing algorithm to minimise the neutral voltage. Therefore, the effect of the network balancing on the phase voltage will be positive. On the other hand, the changes in phase-to-ground capacitances during the network balancing will be small (< 1 A in most cases). Therefore, the change in voltages will be very small during the network balancing. Moreover, loads are connected between phases in RGPDSs and the phase-to-phase voltages will have a minor impact during the network balancing as they mainly depend on the phase-to-neutral voltages. Therefore, the effect of the network balancing on the voltages is not considered in this paper.

5 Boundary conditions, constraints and other conditions

The boundary conditions and the constraints for the proposed balancing technique are discussed in the following subsections.

5.1 Boundary conditions

The main decision variable of this optimisation is the selection of capacitors from available capacitor banks. The boundaries of decision variables depend on the type of available capacitor banks (SCBs or variable capacitors) and SCBs are considered here as discussed earlier. For SCBs, the optimal value of the capacitor to achieve the main goal will be selected from a set of available settings. In this case, the search space of the decision variables are bounded as

$$\Delta I_{abcg(ij)}^{S} \in U_{cap(ij)} \quad \text{for } ij \in U_{sc} \tag{13}$$

where $U_{cap(ij)}$ is the set of available steps or set-points for SCBs located at the section ij.

5.2 Constraints

The constraint for this optimisation is to maintain the balance at the substation under all possible network configurations. It means that the residual current at the substation will be within the threshold under any condition including the current and all possible network configurations. This constraint can be represented by the following equation:

$$I_{r(k)}^{T} < I_{th} \quad \text{for } k = 1, 2, 3, \dots, K \tag{14}$$

where I_{th} is the threshold value or acceptable limit of the residual current (i.e. the maximum allowable unbalance). This threshold I_{th} needs to set based on the sensitivity of the fault detection algorithm on the neutral voltage of the system. It is recommended that the I_{th} will be smaller than the residual current, which will induce a

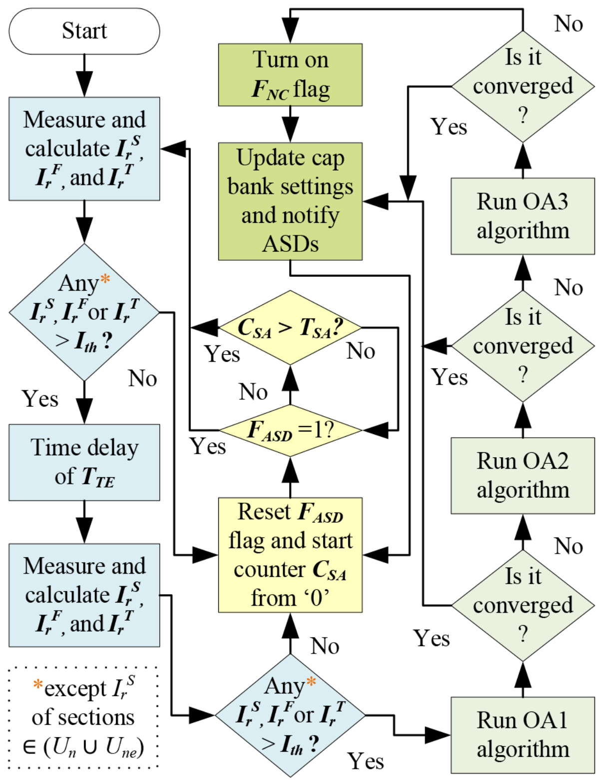

Fig. 4 *Flowchart of the SCADA algorithm*

neutral voltage equal to the threshold neutral voltage for the fault detection algorithm.

Moreover, it is better to maintain the residual currents at all feeders and sections lower than the threshold to further ensure that the effect of change in the network configuration on the system unbalance is small. As a result, the effect of connection or disconnections of a feeder or section on the unbalance at the substation will be minimised. These constraints can be represented as:

$$I^{\mathrm{F}}_{\mathrm{r}(i)} < I_{\mathrm{th}} \quad \text{for } i = 1, 2, 3, \ldots, m \tag{15}$$

$$I^{\mathrm{S}}_{\mathrm{r}(ij)} < I_{\mathrm{th}} \quad \text{for } ij \in U_{\mathrm{sc}} \text{ and } ij \notin U_{\mathrm{ne}} \tag{16}$$

where U_{ne} is the set of sections, which have capacitor bank but not have enough for balancing the respective section. As the constraints presented in (15) and (16) are not an obligatory requirement, these constraints can be relaxed based on the system status.

5.3 Other conditions

In the proposed optimisation, initial conditions are selected in two different ways for initial optimisation and running optimisation to maintain the balance of the system after initial balancing. In the initial optimisation, settings of the capacitor banks are selected based on the unbalance of the respective section. In this case, the settings of the capacitor banks are calculated using (4), where the settings are calculated by minimising (4). For running optimisation, the initial settings of the capacitor banks are selected same as the existing settings to balance the system after any change in the network, as the changes usually occur in one or two sections at a time.

Moreover, the optimisation algorithm stops if it satisfies the boundary conditions, constraints and the average change in the objective function is less than a specific value. However, if the optimisation algorithm does not satisfy the boundary conditions and constraints, it will stop after a certain number of iterations. The threshold value for the average change in the objective function, the number of iterations to stop the algorithm and the number of offsprings can be selected based on the industry requirement. It is worth to mention that the execution time of the optimisation algorithm is not critical in the network balancing as the frequency of balancing the network lies in hours or days. The overall network balancing algorithm is presented in the following section.

6 Network balancing algorithm

An automatic balancing algorithm is developed to balance the system by considering the objectives, boundary conditions and constraints as discussed in previous sections. As discussed earlier, the main balancing algorithm will be embedded with the SCADA system. In this algorithm, the residual currents are measured at different locations on the network to identify the status of the system, i.e. balanced or unbalanced. It is worth to note that residual currents are measured using the automatic switching devices (ASDs), which include circuit breakers (CBs) and relays. These measurements are collected via communication channels. In addition to this SCADA algorithm, another algorithm (ASD algorithm) is developed for ASDs to minimise the cost associated with the communication. Both algorithms are discussed in the following subsections.

6.1 ASD algorithm

The measured unbalances are checked in the SCADA algorithm with a certain time cycle (T_{SA}). The smaller value of T_{SA} is better but it is costly due to the cost of communication to collect data from ASDs. A solution to this problem is to include a small algorithm in the ASDs. The objective of this algorithm is to report the changes in unbalances (at the location of ASDs) to the SCADA system. The ASD algorithm measures the instantaneous residual current (magnitude and angle) at the location of the respective ASD. It is then compared with the residual current at the same location just after the execution of the recent optimisation algorithm within the SCADA system. If any significant change in the residual current is found, it sends a flag ($F_{\mathrm{ASD}} = 1$) to the SCADA for checking the system unbalance. In this case, the communication is required only if any ASD find the unbalance in the system. Another advantage of this algorithm is that it can give an idea of the area, where the shunt capacitors are unbalanced. As a result, the SCADA algorithm can check the unbalance of the specific area only instead of the entire system to further reduce the cost of communication. However, ASDs can only measure the unbalance in the current state while it is also essential to ensure that the system is balanced for other network configurations as well. Thus, it is still required to check the system unbalance regularly even ASDs do not identify the unbalance. In this case, the unbalance can be checked in the SCADA with a much lower frequency. The detailed SCADA algorithm for automatically balancing the network capacitive unbalance is discussed in the following subsection.

6.2 SCADA algorithm

The SCADA algorithm is the main balancing algorithm, which collects information from ASDs and evaluates the necessity of optimisation. The settings of available capacitor banks are then optimised to balance the system if required. The flowchart of the SCADA algorithm is shown in Fig. 4.

At the beginning, the residual currents $i_{\mathrm{r}}^{\mathrm{ASD}}$ at all ASD points are measured. The residual currents for all individual sections are then calculated as

$$i^{\mathrm{S}}_{\mathrm{r}(ij)} = i^{\mathrm{ASD}}_{\mathrm{rb}(ij)} - i^{\mathrm{ASD}}_{\mathrm{re}(ij)} \tag{17}$$

where $i^{\mathrm{ASD}}_{\mathrm{rb}(ij)}$ and $i^{\mathrm{ASD}}_{\mathrm{re}(ij)}$ are the residual currents at the ASDs located in the beginning and the end of the section ij, respectively. In the case of multiple ASDs (for multiple branches) at the end of a section, $i^{\mathrm{ASD}}_{\mathrm{re}(ij)}$ is equal to the summation of residual currents of all ASDs at the end of section ij. It is worth to mention that the residual current of the last section of a feeder is equal to the residual current at the ASD located in the beginning of the section.

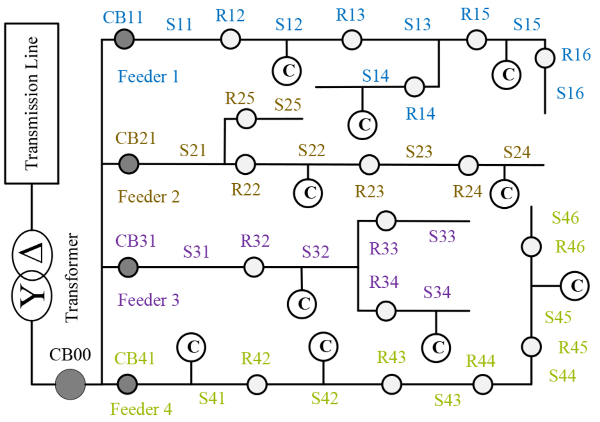

Fig. 5 *Test system based on a real power distribution network*

Moreover, the residual currents for feeders (i_r^F) are equal to the same at the ASDs located in the beginning of the feeders (i.e. feeder CBs). Similarly, the total residual current in the system (i_r^T) is equal to the same at the main CB at the substation. Then, the estimated residual currents at the substation for other network configurations are calculated using (7). In this case, residual currents of the offline sections are approximated with the last measured residual current or the usual unbalance of the section. It is considered that the capacitor banks situated in the offline sections are set to the default settings. The default settings are the settings for which the unbalance of the respective section will be as small as possible and the default settings are updated regularly based on the growth of the system unbalance.

After that, the absolute value of the residual currents at all sections (I_r^S) (except sections $\in (U_n \cup U_{ne})$), feeders (I_r^F) and the substation (I_r^T) are calculated and compared with the threshold value, where U_n is the set of sections with no capacitor bank. If any of these is more than the threshold and continues more than the allowable time limit (T_{TE}), the optimisation algorithm starts to balance the system.

Three optimisation algorithms with different search spaces are included in the SCADA algorithm for balancing the system. The main goal of all these three algorithms is to balance the entire system by optimising the settings of available capacitor banks. These algorithms are named as optimisation algorithm 1 (OA1), optimisation algorithm 2 (OA2) and optimisation algorithm 3 (OA3). Among these optimisation algorithms, OA1 executes first, which uses the available capacitor banks only in unbalanced section/s to balance the entire system. The OA2 starts to balance the system using available capacitor banks only in unbalanced feeder/s if OA1 fails. Finally, the OA3 is used for balancing the entire system using all capacitor banks if both OA1 and OA2 are not converged. The details of these optimisation algorithms are discussed in the following.

6.2.1 OA1: It uses the capacitors only in the unbalanced sections, where residual currents are more than the threshold. Through this OA1, the new settings of capacitor banks are determined by optimising (11) while considering the constraints as presented in Section 5. In this case, the search space is narrowed down to the unbalanced sections only, i.e. for $ij \in U_{us}$ only in (13) with U_{us} as the set of unbalanced sections. In OA1, the settings of the capacitors located in the balanced sections do not change. However, if all sections are balanced (but the system is unbalanced) and the F_{ASD} flag is on, this algorithm checks the location of the ASD device from where the F_{ASD} flag is coming. If the flag comes from a filed relay, all available capacitor banks at the downstream of the respective relay are optimised to balance the system. If the optimisation fails to converge or the F_{ASD} flag is zero or the F_{ASD} flag comes from the feeder's CB or substation's CB, the OA2 starts to balance the system.

6.2.2 OA2: In this algorithm, the available capacitor banks in the unbalanced feeders are optimised to balance the entire system using (11) and considering the same constraints used in OA1. Here, the unbalanced feeder is the feeder, where the residual current at the feeder's CB or any of the section is more than the threshold. For this optimisation algorithm, the search space is limited to the sections of the unbalanced feeders only, i.e. $ij \in U_{uf}$ in (13) with U_{uf} as the set of sections of unbalanced feeders. In OA2, the settings of the capacitors located in the balanced feeders do not change. If all feeders and sections are balanced but the substation is unbalanced and the F_{ASD} flag is on, this algorithm checks the location of the ASD device from, where the flag comes from. If the F_{ASD} flag comes from any ASD of a feeder, the respective feeder is identified as an unbalanced feeder in this case. If the OA2 is failed to converge or the F_{ASD} flag is zero or the F_{ASD} flag comes from the substation CB, the OA3 performs.

6.2.3 OA3: If both OA1 and OA2 are failed to balance the system, OA3 executes, where the settings of all capacitor banks in the system are optimised to balance the system using (11) and considering the same constraints. The entire search space is used for this optimisation.

Finally, the settings of the capacitor banks are updated with the optimised settings and notify ASDs if any of the optimisation algorithms is converged. However, if none of them are converged, still the capacitor bank settings are updated with the optimised settings from OA3 and a non-convergence flag (F_{NC}) is turned on to notify the responsible person for manually investigating the system unbalance.

After the first iteration, the SCADA balancing algorithm runs with a pre-defined time cycle T_{SA} to check the system unbalance and balance it if requires. However, the SCADA algorithm will instantly check the system unbalance if the F_{ASD} flag is received from any ASD. In the case of a non-convergence scenario, the lower value of T_{SA} and T_{TE} can be used to run the SCADA balancing algorithm more frequently. Also, this algorithm can run frequently during the total fire ban (TFB) days to ensure the system is balanced at all time. This will ensure that the sensitivity of the fault detection algorithm is good enough to detect all faults, which also helps to mitigate bushfires.

7 Results and discussions

The effectiveness of the developed scheme, as presented in this paper is tested on several real power distribution networks through simulation using *MATLAB/SimpowerSystem*, where similar results are observed. In this section, results are analysed for the network as shown in Fig. 5. This is a 22-kV medium-voltage (MV) distribution network. There are four feeders in this system with several sections in each feeder. The sections are defined as the part of a feeder from a CB or relay to the next relay/s at the downstream or end of the feeder and the name of the section is defined as the number of the originating CB or relay. For example, section S13 is the area from R13 to R14 and R15 in Fig. 5. In this system, the three-phase SCBs are available on the following sections: S12, S14, S15, S22, S24, S32, S34, S41, S42 and S45. The available set-points of all capacitor banks are the same, which are (set-points for each phase): 0, 42, 56, 59, 81, 89, 149, 170, 179, 208, 234, 238, 268, 327 and 416 mA. The threshold for the residual current is considered as 100 mA, which means that the system is considered as a balanced system if the residual currents are under 100 mA. The developed technique is tested for different scenarios. Among these, two case studies are presented in the following to validate its performance.

7.1 Case study 1: disconnections of sections to the system

In this case study, the performance of the proposed balancing technique is evaluated for the disconnection of sections after balancing an unbalanced system. It is considered that the system as shown in Fig. 5 is unbalanced from $t = 0$ to 20 min and the proposed network balancing technique is employed to balance this

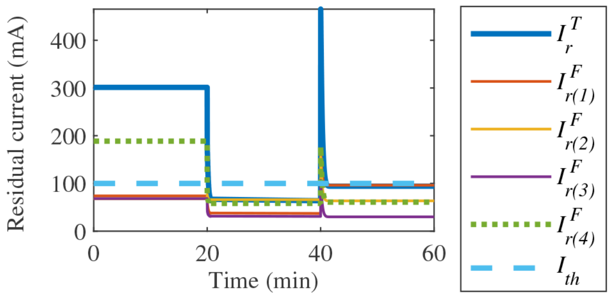

Fig. 6 *Residual currents at feeders and the substation for Case 1*

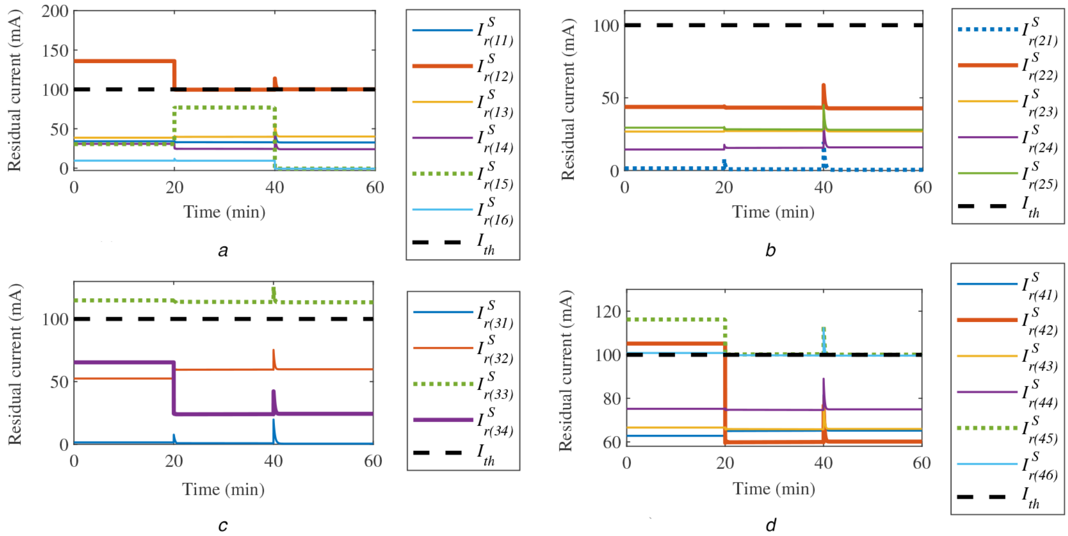

Fig. 7 *Residual currents at all sections for Case 1*
(a) Currents of sections of Feeder 1, ***(b)*** Currents of sections of Feeder 2, ***(c)*** Currents of sections of Feeder 3, ***(d)*** Currents of sections of Feeder 4

Table 1 Existing and optimised capacitor settings for case 1

Location of the cap banks		Existing settings, mA			Optimised settings, mA		
Feeder	Section	*A*	*B*	*C*	*A*	*B*	*C*
1	S12	0	0	0	268	81	42
	S14	0	0	0	179	238	234
	S15	0	0	0	59	149	170
2	S22	0	0	0	0	0	0
	S24	0	0	0	0	0	0
3	S32	0	0	0	149	81	56
	S34	0	0	0	42	81	89
4	S41	0	0	0	234	234	238
	S42	0	0	0	234	234	149
	S45	0	0	0	179	0	238

system at $t = 20$ min. At $t = 40$ min, some portions of the network (last two sections of Feeder 1) in Fig. 5 are intentionally disconnected to observe the system unbalances in the case of disconnection of sections after balancing the system.

The residual currents at the substation and feeders are shown in Fig. 6 and the same for sections in different feeders are shown in Fig. 7. From both Figs. 6 and 7, it can be observed that there are unbalances within the system as the residual currents at the substation (I_r^T); Feeder 4 ($I_{r(4)}^F$); section S12 ($I_{r(12)}^S$) of Feeder 1; section S33 ($I_{r(33)}^S$) of Feeder 3; and sections S42 ($I_{r(42)}^S$), S45 ($I_{r(45)}^S$) and S46 ($I_{r(46)}^S$) of Feeder 4 are more than the threshold value (100 mA) during $t = 0$ to 20 min. Therefore, all these sections (i.e. S12, S33, S42, S45 and S46) are unbalanced sections and OA1 is first executed to balance the entire network using only available capacitor banks in these sections. The setting of other capacitor banks located in the balanced sections will remain unchanged. Among these unbalanced sections, all sections (except sections S33 and S46) have capacitor banks as shown in Fig. 5 and all these existing capacitor banks are optimised to balance the system. However, due to the limited number of the capacitor banks in the unbalanced sections, OA1 was not sufficient to balance the network, and OA2 was needed.

After looking into the unbalances in different sections and feeders, it can be concluded that all feeders except Feeder 2 are unbalanced from $t = 0$ to 20 min. Hence, OA2 starts at this point for balancing the entire network using capacitor banks in all unbalanced feeders. After utilising OA2, the system balance is achieved by optimising the capacitor banks located in Feeders 1, 3 and 4. The existing settings of all SCBs was 0 mA and from OA2, the optimised settings (for three phases *A*, *B*and C, respectively), of the SCBs are shown in Table 1. The settings of SCBs located at Feeder 2 remained unchanged as this is a balanced feeder. These new optimal settings are applied at $t = 20$ min. After utilising OA2, it is found that the system is balanced and all capacitor banks located in Feeders 1, 3 and 4 are optimised.

From Fig. 6, it can clearly be seen that the residual currents at all feeders and the substation are now under the threshold as the new optimal settings of capacitor banks are applied at $t = 20$ min. However, the residual current ($I_{r(33)}^S$) in section S33 of Feeder 3 is still above the threshold (as shown in Fig. 7*c*) as there is no capacitor bank in this portion of the network. Nonetheless, it is still acceptable as the residual currents at all feeders and the substation are well below the pre-specified threshold.

At $t = 40$ min, two sections (sections S15 and S16) of Feeder 1 are intentionally disconnected from the network in Fig. 5 in order to further evaluate the effectiveness of the developed network balancing technique due to such disconnections. Since these two sections are disconnected, the residual currents ($I_{r(15)}^S$ and $I_{r(16)}^S$) for these two sections became zero, which can also be seen from Fig. 7*a* at the instant of $t = 40$ min and onward. Such disconnections would affect the overall network balance. From Fig. 6, it can be

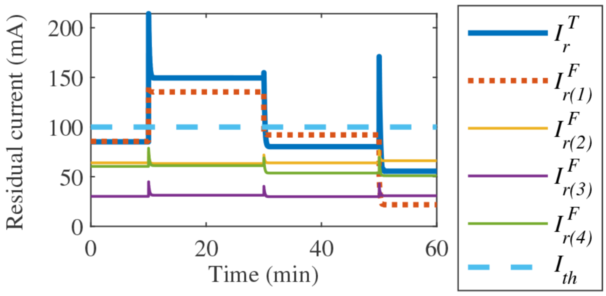

Fig. 8 *Residual currents at feeders and the substation for Case 2*

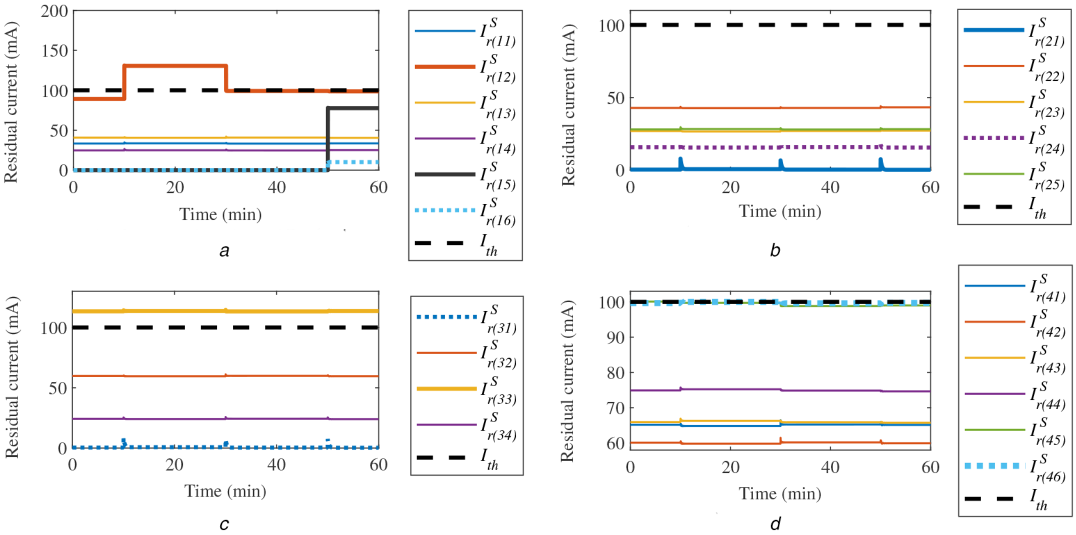

Fig. 9 *Residual currents at all sections for Case 2*
(a) Currents of sections of Feeder 1, ***(b)*** Currents of sections of Feeder 2, ***(c)*** Currents of sections of Feeder 3, ***(d)*** Currents of sections of Feeder 4

Table 2 Existing and optimised capacitor settings for case 2

Location of the cap banks		Existing settings, mA			Optimised settings, mA		
Feeder	Section	*A*	*B*	*C*	*A*	*B*	*C*
1	S12	268	81	42	268	0	42

observed that the residual currents of Feeder 1 ($I_{\rm r(1)}^{\rm F}$) and the substation ($I_{\rm r}^{\rm T}$) have changed due to the disconnection of these sections but their values are still under the threshold.

From the above discussions, it is noticed that the developed scheme ensures the network balancing with minimum switching of capacitor banks. In this case study, the balance is achieved without changing the settings of the capacitor banks located in Feeder 2 even the unbalance was too high. Therefore, it is evident that the proposed balancing technique is capable to balance an unbalanced system and maintain the system unbalance under a pre-defined value after disconnection of sections from the network.

7.2 Case study 2: connections of sections to the system

In this case study, the following scenarios are considered:

- The system is balanced from $t = 0$ to 10 min.
- The system is intentionally unbalanced by adding a single-phase line in a section at $t = 10$ min and this continues until $t = 30$ min without employing the proposed balancing technique.
- The network balancing technique is employed at $t = 30$ min to balance the system.
- Finally, two additional sections are connected at $t = 50$ min and the network unbalance is observed.

Based on the above scenarios, the entire system is initially (from $t = 0$ to 10 min) considered as balanced, which can also be seen from Figs. 8 and 9. All sections (excluding section S33, which does not have a cap bank) along with the substation and feeders are balanced as the residual currents are below the threshold.

From Fig. 8, it can be seen that the residual currents at the substation and Feeder 1 have crossed the threshold at $t = 10$ min and similarly, Fig. 9*a* shows that the residual current of section S12 ($I_{\rm r(12)}^{\rm S}$) in Feeder 1 also exceeded the threshold at the same time because of intentionally adding an extra single-phase line in this section. At $t = 30$ min, the OA1 is executed for balancing the entire system and the system becomes balance at the first instance as the unbalance was only in one section, i.e. section S12 (please see Figs. 8 and 9). The initial settings of all SCBs are selected the same as the settings at the end of case study 1 and the new optimised settings (at different phases) of the SCB located at section S12 are 268, 0 and 42 mA. The settings of other capacitor banks are remained unchanged as they are located in balanced sections and OA1 algorithm is converged, i.e. system balance is achieved by optimising the settings of the capacitor banks of the unbalanced section (S12) only. The optimised settings of the capacitor banks along with existing settings in section S12 of Feeder 1 are shown in Table 2.

Finally, two new sections (sections S15 and S16 of Feeder 1) are connected to the system at $t = 50$ min, which sections were not initially connected, i.e. the residual currents ($I_{\rm r(15)}^{\rm S}$ and $I_{\rm r(16)}^{\rm S}$) for these sections are zero before $t = 50$ min, which can also be seen from Fig. 8*a*. At this instant, the residual current at the substation is changed, but it is under the threshold, which can be clearly seen from Fig. 8 (i.e. system is balanced). In this case study, it is also noticed that the unbalance at the substation is reduced at the substation while connecting sections at $t = 50$ min, as it is considered that the weight factor of the unbalance at the substation for the full network configuration (where all sections are connected) is higher than other network configurations. Moreover,

Table 3 Average unbalance currents with different weight factors after executing optimisation algorithm **OA1**

Average current	$I^{Ta}_{r(av)}$, mA	$I^{F}_{r(av)}$, mA	$I^{S}_{r(av)}$, mA
$W_T > W_F > W_S$	60.42 (75.05)	79.35	73.36
$W_F > W_T > W_S$	73.59 (89.85)	57.37	78.55
$W_S > W_T > W_F$	68.39 (80.51)	71.74	59.82

[a]Unbalance in usual network configuration (other configurations)

Table 4 Average unbalance currents with different weight factors after executing optimisation algorithm **OA2**

Average current	$I^{Ta}_{r(av)}$, mA	$I^{F}_{r(av)}$, mA	$I^{S}_{r(av)}$, m
$W_T > W_F > W_S$	45.23 (53.85)	67.37	79.54
$W_F > W_T > W_S$	52.91 (58.45)	55.89	74.46
$W_S > W_T > W_F$	53.55 (57.59)	63.62	63.73

[a]Unbalance in usual network configuration (other configurations).

Table 5 Average unbalance currents with different weight factors after executing optimisation algorithm **OA3**

Average current	$I^{Ta}_{r(av)}$, mA	$I^{F}_{r(av)}$, mA	$I^{S}_{r(av)}$, mA
$W_T > W_F > W_S$	41.38 (59.81)	58.84	66.17
$W_F > W_T > W_S$	48.13 (58.75)	51.49	64.76
$W_S > W_T > W_F$	52.85 (55.19)	55.53	59.82

[a]Unbalance in usual network configuration (other configurations).

it is noticed in Fig. 9*a* that the unbalances of the new sections (sections S15 and S16) connected at $t = 50$ min are small. The reason behind small unbalances at new sections is that the default settings are applied to the capacitor banks, which are located in the offline sections. Simulation results clearly demonstrate that the proposed technique can be successfully applied while connecting new lines or sections within the network.

7.3 Impacts of the weight factors

In this paper, weight factors are used to prioritise one objective over others. Several case studies are conducted to justify the concept, where it is considered in all case studies that two sections, one feeder and the substation unbalances are above the threshold. Here, the weight factors for different cases are considered as follows: case 1: $W_T = 3W_F = 5W_S$, case 2: $W_F = 3W_T = 5W_S$ and case 3: $W_S = 3W_T = 5W_F$. Table 3 provides the average unbalance currents at different parts of the network after executing the optimisation algorithm **OA1** with different weight factors. Here, $I^{T}_{r(av)}$, $I^{F}_{r(av)}$ and $I^{S}_{r(av)}$, are the average unbalance currents at the substation, feeder and section level, respectively. It is noticed from this table that the weight factors have some impacts on the unbalance current at the substation, feeder and section levels. From Table 3, it is clear that the unbalance current at the substation is lowest for the first case among three cases, i.e. when $W_T > W_F > W_S$, as the unbalance current at substation is prioritise over other locations in Case 1, where unbalance currents at other locations of the network are prioritise in other cases. Similarly, the average unbalance current at the feeder level is lowest when $W_F > W_T > W_S$, where feeder unbalance is prioritised. Moreover, the average unbalance current is lowest at the section level when $W_S > W_T > W_F$, as the section unbalance is prioritised in this case. However, the relation between average unbalance currents at different locations of the network in a given case study does not follow the priority within them, as the availability of the capacitor banks are different in the different parts of the network.

The average unbalance currents at different locations of the network for different weight factors after executing the optimisation algorithms **OA2** and **OA3** are presented in Tables 4 and 5, respectively. Similar results are observed in Tables 4 and 5 comparing Table 3. The only exception is noticed in Table 5 that the average unbalance current at the substation in other network configurations is lowest for the second case instead of the first case, as the weight factor for the unbalance at the substation for other network configurations is considered half of the current network configuration. Finally, it can be concluded that the priorities of any objective in the proposed network balancing technique can be assigned using appropriate weight factors.

8 Conclusion and future work

An automatic network capacitive balancing technique is developed to balance the shunt capacitances in RGPDSs in this paper. In this technique, the network capacitive balance is achieved with a limited number of three-phase SCBs, which are distributed throughout the system. The settings of available capacitor banks are optimised to balance the entire system in which the system unbalance is under the threshold for the current network configuration as well as for all other possible configurations. Different case studies are conducted to validate the effectiveness of the proposed network balancing technique. Simulation results depict that the system balance is achieved with the minimum number of switching for capacitor banks, which contributes to enhance the lifetime of the capacitor bank.

The proposed balancing technique is designed for the radial distribution system, however, it can be further extended for the mesh-type distribution networks. The effect of harmonics is not considered in this paper, which can be included in the future work. Furthermore, the developed algorithm can be improved by optimally selecting the priority index for a specific network and industry requirements.

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