Active distribution network with efficient utilisation of distributed generation ancillary services

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Abstract: This study introduces an active distribution network with high penetration of inverter-based distributed generations (IBDGs) to improve the steady state, dynamic and transient performance of the distribution network. The size and location of the IBDGs, capacitor bank, on-load tap changers position and voltage regulator set points have been optimised to minimise the system losses, improve voltage profile and maximise the dynamic reactive power reserve. In addition to that, the adaptive master/slave roles are deployed in planning the active distribution network to achieve the best utilisation of each device based on its capability and response time in steady state, dynamic and transient operation. Indeed, the optimisation algorithm allows the IBDGs to operate in an inductive mode of operation during steady state resulted in maximising the dynamic reactive power reserve. Consequently, the IBDGs react with large dynamic margin in response to grid fault leading to enhanced voltage recovery and improved transient response. A comprehensive system optimisation and transient analysis are carried out to demonstrate the performance of the distribution network for enhancing the voltage profile, increasing the penetration level of renewable energy distributed generation, IBDGs, and improving the transient recovery in response to severe grid fault.

1 Introduction

With global acceptance of green energy and also the deregulation of the energy sector as the future of electricity supply and delivery, policies are being formulated to increase the penetration levels of distributed generation (DG) into power systems. This surge in penetration level will pose some challenges to power system planning and operations. To deal with this, the next-generation distribution networks (DNs) should be efficient and robust enough to deal with these challenges such as the bi-directional flow of power since they were traditionally designed for unidirectional flow. This can lead to a voltage rise at the point of common coupling (PCC) [1–4], hence affecting the system operation.

Mitigating these challenges has triggered extensive research focusing on two main areas. While some investigators are looking at the introduction of smart grid technologies into DNs, others are looking into the capabilities of DGs that can improve the performance of DNs. According to Pepermans et al. [5], DGs can have a positive impact on power system operations such as loss reduction and the provision of ancillary services such as voltage and frequency control. In addition to that, eliminate the cost of transporting electrical power from various long distances over transmission lines and also the losses associated with them as compared with centralised generation. However, these benefits may be realised if they are not sited and coordinated in an effective manner. Hence, efficient utilisation of DGs’ resources makes the idea of moving from a passive to the concept of active network management scheme (ANMS) is very promising for implementation in the DNs.

The passive DNs show limitation on the high penetration of DGs due to their fixed power factor (PF) operation and the implemented secondary voltage control (VC) based on line drop compensation for controlling the OLTCs [1, 6, 7]. The need for high penetration of DGs drives the researchers to investigate the planning of DN based on the ANMS. Therefore, alternative control strategies for DGs such as using the inverter-based DGs (IBDGs) have been utilised to allow high penetration of DGs using coordinated VC among DGs, compensator devices, OLTCs and voltage regulators to achieve desirable steady state performance [10]. Moreover, the power curtailment from DGs has been incorporated in the ANMS to mitigate the overvoltage problems in the DN and it is compared with the other approach such as ‘last-in-first-out’ reported in [2].

The introduced ANMSs in the literature have emphasised only the steady state performance in the planning with various optimisation algorithms. The steady state voltage problem was one of the main concerns to accommodate high penetration of DGs [11–12]. In this context, the different control strategies of DGs employing variable PF control (PFC), power curtailment and coordinated VC have been analysed in the view of maximising the penetration of DGs [6, 13–17] and also ensure sufficiency of reactive power in the network at all times. This alleviated the voltage instability, which is mainly caused by deficient reactive power curtailment from DGs, beyond which there could be a voltage rise. To eliminate this, the authors of [15] proposed a combined PFC and VC method. This allows the DG to operate in PFC mode when the voltage at the PCC is within the permissible range and

Nomenclature

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\begin{align*}
V_i, \theta_i & \text{ voltage magnitude and the angle at the } i^{\text{th}} \text{ bus} \\
T & \text{ tap setting of the on-load tap changers (OLTC) and VR} \\
Q_{DG_i}, P_{DG_i} & \text{ reactive and active power of DG at the } i^{\text{th}} \text{ bus} \\
PF_{DG} & \text{ power factor of DG} \\
P_{\text{loss}}, Q_{\text{loss}} & \text{ active and reactive power loss of the } i^{\text{th}} \text{ branch} \\
V_{ij}, B_{ij} & \text{ } i^{\text{th}} \text{ element of the } j^{\text{th}} \text{ bus matrix} \\
P_{Di}, Q_{Di} & \text{ active and reactive load demand at the } i^{\text{th}} \text{ bus} \\
P_{Gi}, Q_{Gi} & \text{ active and reactive power generated at the } i^{\text{th}} \text{ bus} \\
P_{ij}, Q_{ij} & \text{ active and reactive power flows on the } i^{\text{th}} \text{ line} \\
S_{DG_i} & \text{ MVAr rating of DG at the } i^{\text{th}} \text{ bus} \\
S_{ij} & \text{ thermal limit of the } i^{\text{th}} \text{ line} \\
Q_{C} & \text{ reactive power supplied by CAPs’ bank}
\end{align*}
\]
switch to VC mode when the voltage limits are violated. This work, however, did not include the operation of on-load tap changers (OLTCs) in the analysis. Investigators of [16] designed a new control scheme for OLTC to eliminate the problems with the existing line drop compensation method especially with the integration of DGs. The problem with most of these OLTC schemes is the Tap limits and hence not sufficient to regulate the voltage. Also, a sensitivity analysis was involved in the installation of DGs considering the type, capacity and location have been tested to overcome the shortcoming of the random approach in integrating DGs. Consequently, most of the ANMS studies considered the fixed location of DGs and carried out the optimisation for enhancing the steady state performances such as maximising the DG penetration, minimising system losses and improving the voltage profile [13, 18, 19]. Although the proposed studies for ANMS achieved enhanced steady state performance the transient performance does not guarantee and it may result in voltage instability especially with high penetration of dynamic loads.

Subsequently, optimally siting and sizing of DGs in DN as have been investigated by different authors. These included different optimisation techniques with diverse objective functions, ranging from a single objective to multi-objectives and constraints to utilise DGs to improve power system operation and performance. These objectives vary from economic to technical and to environmental needs of the network. In [20–25], the optimal placement of DGs to reduce active losses and improve the voltage profile is proposed, others [25, 26] also focused on using DGs to improve the voltage stability of the network. Also, the optimal sizing and allocation of a shunt capacitor (CAP) are discussed in [27]. However, most of the work done in this field focused on using the DGs to improve the steady state performance of the network such as losses and voltage profiles. However, the transients’ characteristics of the DN are not considered in the system optimisation.

Voltage instability or its severe form (voltage collapse) occurs when there is not enough reactive power reserve (RPR) within the period of contingency. Also, it can occur when any of the devices reach their reactive power limit thereby triggering a cascading effect [28]. Thus, the amount of RPR is a measure of the voltage stability margin (VSM). The utilisation of the RPR margin during contingencies is dependent on the response time of each reactive power resource, in other words, a fast occurring dynamics on the power grid such as fault conditions and the intermittent nature of DGs will require fast and dynamic RPR (DRPR) margin to improve and restore the voltages across the network during these periods, consequently improving the transient performance of the network [12, 29]. This fast DRPR is provided by synchronous generators, condensers and inverter-based devices such as STATCOM etc., which are traditionally not available in the DN [30–37]. Thus there is a need to incorporate DRPR into DN planning to help improve the transient performance of the network.

Various RPR management schemes are proposed in [28, 38, 39]. In [38], the multi-objective optimal power flow and Bender's decomposition to maximise RPR is introduced. In [28], a convex quadratic optimisation-based approach was used to enhance critical RPR, while the authors of [39] used a multi-objective-based fuzzy method. Choi et al. used sensitivity analysis to estimate the effective RPR that can be utilised during severe contingencies [40]. However, all these analysis and methods did not consider the response time and type of RPR, optimal allocation of IBDGs and the coordinated VC. Therefore, this study introduces an integrated optimisation algorithm for planning the DN with high penetration of DGs and employing the ANMS to tackle the steady state and transient operational challenges.

In this work, the ancillary services provided to the grid are the VC and reactive power compensation. This was achieved by utilising the reactive power resources of the IBDGs. Both the IBDGs and CAP banks are optimally allocated based on steady state and transient indices for the aim of improving the voltage profile, minimising the system losses and maximising the fast DRPR to react effectively during severe system disturbances. Consequently, the optimisation algorithm will operate the IBDGs in the inductive mode of operation to maximise the DRPR during steady state. This optimisation and transient studies are carried out on the 16-bus UK Generic Distribution system (UKGDS) using a genetic algorithm (GA) and PSCAD/EMTDC, respectively, to verify the proposed approach of ANMS for enhancing the transient response.

2 Problem formulation of system optimisation

This section discusses the methodology utilised by ANMS to optimise the location and size of DG and CAP bank. The proposed problem is a multi-objective optimisation problem with three objective functions. It is a mixed integer problem (MIP) since some of the decision variables such as bus location are constrained to integers. Solving the MIP with interior point methods has not been efficient [41]. Thus, it is paving way for the increasing application of heuristic techniques to power systems optimisation problems in recent years. This is due to their ability to avoid local minimum [42, 43], especially with MIP. In this study, GA is used, which is a heuristic technique designed to emulate the processes of natural evolution. It does not require derivatives as other conventional tools do. Hence making it converge faster. The three objective functions and system constraints are defined as follows.

2.1 Objective functions

2.1.1 Voltage profile: The minimisation of voltage profile index ($V_{ip}$) is used as an indication of voltages’ improvement at all buses as given in (1)

$$V_{ip} = \sqrt{(\Delta V_i^1 + \Delta V_i^2 + \cdots + \Delta V_i^m)}.$$  

where $\Delta V_i = (V_i - 1)$.

2.1.2 System losses: The total losses in the DN with $m$ total number of transmission lines can be expressed as

$$\text{minimising } L = \sum_{k=1}^{m} \sqrt{P_{\text{loss } k}^2 + Q_{\text{loss } k}^2}.$$  

2.1.3 Maximising DRPR: This function allows the IBDGs to operate in inductive mode during steady state to maximise the DRPR based on the power balance equation expressed in (3)

$$Q_{DG} - Q_{CH} = \sum_{j=1}^{N} V_j (G_{ij} \sin (\delta_j - \delta_i)) - B_{ij} \cos (\delta_j - \delta_i).$$  

For $i = 0, 1, \ldots, N$. Since the DG is treated as a negative load, the total (net) reactive load $Q_{DN}$ at demand at bus $i$ after the DG is connected is expressed in (4)

$$Q_{DN} = Q_{CH} - Q_{DG}.$$  

where $Q_{DG}$ is the reactive power supplied by the DG and $Q_{CH}$ is the reactive load demand at bus $i$ before the DG was connected.

By substituting (4) into bus equation (3)

$$Q_{DG} = -\sum_{j=1}^{N} V_j (G_{ij} \sin (\delta_j - \delta_i)) - B_{ij} \cos (\delta_j - \delta_i)$$  

$$-Q_{CH} + Q_{DN}.$$  

Reactive power from the DG is a function of the PF and active power generated by the DG which is expressed as

$$Q_{DG} = P_{DG} \tan (\arccos (\varphi)),$$  

where $\cos \varphi = P_{DG}/S_{DG}$ satisfying the condition
### Table 1: GA parameters

| no. of generation | 600          |
|-------------------|--------------|
| population size   | 200          |
| selection function| Stochastic   |
| crossover function (rate) | scattered (0.8) |
| mutation function | constraint dependent |
| function tolerance | $10 \times 10^{-6}$ |
| stall generations | 550          |

0.95 ≤ $P_{DGi}/S_{DGi}$ ≤ 1. \hspace{1cm} (7)

The IBDGs will be allowed to operate from 0.95 PF lagging to unity PF [36]. These objective functions will be subjected to the following constraints:

1. **Bus-voltage constraints**

$$V_{i_{min}} \leq V_i \leq V_{i_{max}}.$$ \hspace{1cm} (8)

where $V_{i_{min}}$ and $V_{i_{max}}$ are the minimum and maximum voltage of the $i$th bus, respectively. The minimum value is 0.94 pu and the maximum value is 1.06 pu [37].

2. **Tap constraints**

$$T_{i_{min}} \leq T \leq T_{i_{max}}.$$ \hspace{1cm} (9)

where $T_{i_{min}}$ and $T_{i_{max}}$ are the minimum and maximum tap position, respectively. The minimum tap position is 0.85 pu and the maximum is 1.05 pu [37].

3. **DG PF constraints**

$$PF_{DG_{min}} \leq PF_{DG} \leq PF_{DG_{max}}.$$ \hspace{1cm} (10)

where $PF_{DG_{min}}$ and $PF_{DG_{max}}$ is the minimum and maximum PF for the DG, respectively. The PF will be ranging from 0.95 lagging to 0.95 leading [44].

4. **DG reactive power constraints**

$$Q_{DG_{min}} \leq Q_{DG} \leq Q_{DG_{max}}.$$ \hspace{1cm} (11)

where $Q_{DG_{min}}$ is the maximum reactive power absorbed and $Q_{DG_{max}}$ is the maximum reactive power supply by the DG. This will be determined by the DG active power output constrained by the PF limits

5. **Shunt CAP reactive power constraints**

$$0 \leq Q_c \leq Q_{c_{max}}.$$ \hspace{1cm} (12)

where $Q_{c_{max}}$ is the maximum reactive power supply by the CAP bank. The maximum total shunt compensation is assumed to be 80% of the total amount of reactive power loads on the system as the operator defined value.

6. **Thermal limits constraints**

$$\sqrt{P_{i_{j}}^{2} + Q_{i_{j}}^{2}} \leq S_{i_{max}}.$$ \hspace{1cm} (13)

The maximum thermal limit values for the transmission lines were obtained from the test system [45].

7. **Power balance constraints**

$$P_{DG_i} - P_{th} = V_j N \sum_{j=1}^{N} V_j (G_{i,j} \cos(\delta_{i,j} - \delta_j) + B_{i,j} \sin(\delta_{i,j} - \delta_j)).$$ \hspace{1cm} (14)

$$Q_{DG_i} - Q_{th} = V_j N \sum_{j=1}^{N} V_j (G_{i,j} \sin(\delta_{i,j} - \delta_j) - B_{i,j} \cos(\delta_{i,j} - \delta_j)).$$ \hspace{1cm} (15)

### 2.2 Optimisation structure

This multi-objective problem will be solved using the weighted sum approach. This involves mathematically summing all the objective functions multiplied by their appropriate weighting factors to obtain a single equation. The assigned weights ($w_i$) depend on how relevant the function is to the distribution system operator. As mentioned earlier, GA has been utilised in this work to optimise the location and size of DGs as well as the static VAR compensation (CAPs’ bank). The parameters of the GA used for the simulation are shown in Table 1.

This optimisation structure relies on two layers. The first layer is used to optimise the system in the view of maximising the penetration of DGs, identifying the location and capacity as well as the required reactive power compensation (CAP banks), positions of OLTC and voltage regulators settings. Also, the optimisation will consider the response time of each reactive power resource in improving the system performance by allowing the IBDG to operate in inductive mode while OLTC and CAPs during steady state. This is to maximise the fast DRPR of IBDG to be utilised during the transient. Then, the optimised parameters are used in the second optimisation layer to identify possible optimal operating points (reactive power points) of IBDGs considering a variable active power output of IBDG and different loading conditions. This will be used to develop a PQ chart as further explained in Section 4.2 to serve as a guide to the DSO.

To maximise the DRPR to be utilised during transient's state, the IBDG must operate in inductive mode during steady state. Hence reactive power supplied by the IBDG ($Q_{DG}$) must be minimised in the system optimisation (steady state) since $Q_{DG}$ is negative for the inductive mode and positive for the capacitive mode. Thus, the aforementioned objective functions are combined as

minimising $z = w_1 V_i + w_2 L + w_3 Q_{DG}$ \hspace{1cm} (16)

where $\sum_{i=1}^{3} w_i = 1$.

The multi-objective optimisation function will be solved according to the flow chart shown in Fig. 1.

### 3 Power system description and components

The ANMS is implemented and tested in the 16 bus UKGDS system. The 33 kV DN is fed from a 132 kV transmission network. The total base load is considered as 38.16 MW and 7.74 MVAr. The test system comprises a voltage regulator (VR) between buses 8 and 9, which is modelled as an autotransformer with tap changers. The maximum and minimum tap position of the substation OLTC and the VR are 0.85 and 1.05 pu, respectively.

#### 3.1 Switched shunt CAPs

The shunt CAPs are modelled as constant negative reactive power load. Four shunt CAP banks are to be optimised in this study. The amount of MVAr is varied incrementally from 0 in steps of 0.2 MVAr to maximum amount of shunt compensation required.

#### 3.2 Photovoltaic (PV) power system model

Three PV-based DGs are considered for system optimisation. The PV systems are integrated into the DN through 0.69/33 kV transformers. The PV front-end converter (PVFEC) and inverter convert the DC power from the PV module to AC. The PVFEC executes the maximum power point tracking while the inverter controls the grid output voltage and power delivered to the DN. These power electronic devices also decouple the PV modules from the grid and isolate them from the grid faults. Fig. 2 shows the basic diagram of a PV cell. The output current of the cell ($i$) can be expressed as a function of the output voltage ($V$) as follows:

$$i = \frac{I_{th} - I_0 - V + iR_s}{R_{sh}}.$$ \hspace{1cm} (17)
where the current through the diode ($I_D$) can be expressed as

$$I_D = I_o e^{(q(V + iR_s)/kA(T_c - ΔT))} - 1),$$

(18)

Also, the photon current ($I_{ph}$) can be expressed as

$$I_{ph} = \frac{S_i}{S_r} I_r (1 + α(T_r − T_c)).$$

(19)

Therefore, the generated power from the PV module depends on the solar irradiance ($S_i$) and difference between the reference temperature ($T_r$) at standard test conditions (STC) and the cell temperature ($T_c$). $I_o$ represents the diode saturation current. These and other parameters are provided in the Appendix. The grid side converter (GSC) is sized with consideration of PF range of ±0.95 so that the current rating of the converter is determined accordingly.

The PV controller consists of decoupled outer and inner control loops to control both the active and reactive power output independently as shown in Fig. 3 [12]. Controlling the $I_{qref}$ signal controls the reactive power output of the inverter while active power is controlled by the $d$ component. Since much priority is given to the active power generation, the $I_{qref}$ signal generated by the anticipated grid voltage ($V_r$) is controlled according to (19). This depends on the inverter capacity ($I_r$). The measured current signal transformed into the $dq$ reference frame is compared with $I_{dref}$ and $I_{qref}$ signals, respectively. Then, these error signals serve as inputs to the current regulators which generate the reference output voltage ($V_{abc}$) for the GSC after applying park transformation from $dq$ to $abc$.

$$I_{qref} ≅ I_{qref}, \quad I_r > \sqrt{I_{dref}^2 + I_{qref}^2},$$

$$I_r ≤ \sqrt{I_{dref}^2 + I_{qref}^2}.$$  

(20)

4 Performance of ANMS

To demonstrate the effectiveness of the proposed approach in optimally allocating and sizing of IBDGs and CAPs’ bank for improving the transient response of the DN during disturbances, the loading condition of the test system shown in Fig. 4 is increased by 90% of the total rating increasing the flows through the transmission lines. Therefore, the following assumptions and measures are considered:

1. The DG is modelled as the negative load in the load flow analysis. DGs and CAPs’ bank can be installed anywhere within the distribution system with the exception of a substation bus, which is also the slack bus thus no geographical limitation will be observed.

2. The maximum total shunt compensation is assumed to be 80% of the total amount of reactive power loads on the system as the operator defined value. Equal rating is assigned to each CAP.

3. The maximum and minimum permissible voltage for the system is 1.06 and 0.94 pu, respectively. The DGs will be allowed to operate between 0.95 lagging to 0.95 leading PF.
4. The test system in Fig. 4 is implemented in MATPOWER while considering detailed information of the test system as obtained from [37].

The following two scenarios are developed to demonstrate the performance of ANMS:

**Scenario 1:** It is created to represent the base case at which DGs and CAPs’ bank is optimally allocated to only improve the steady state performance (minimising losses and improving voltage profile) as discussed in the literature. Also, the IBDGs are operated at unity power with no reactive power participation which is the current practice in most of the DNs.

**Scenario 2:** A third objective function is added to the base case 1 by allowing the reactive power participation from IBDGs in steady state and during system disturbance. The multi-objective optimisation is carried out while considering equal weights assigned to all the three objective functions.

Both scenarios 1 and 2 have been presented to illustrate and evaluate the performance of the proposed method. However, optimisation parameters (optimal voltage profile requirements, system losses, RPR) can be tuned according to power system planners’ requirements. Also, the weights in the multi-objective function would eventually be fixed according to the conditions and experience with the characteristics of a given system.

The results obtained from the two optimisation cases are then implemented and analysed in PSCAD/EMTDC to validate the system optimisation results and also demonstrate the transient performance in response to three phase-to-ground faults applied at instant 5 s and last for 150 ms at bus 5 with 100% static load. The performance by employing the dynamic loads (induction motors) is also evaluated to demonstrate the transient stability enhancement.

4.1 Evaluation of system optimisation

The optimisation results for scenarios 1 and 2 are shown in Tables 2 and 3, respectively. The results show the optimal size and locations of the CAP banks and IBDGs as well as the OLTC and VR settings to ensure the minimum system losses, enhanced voltage profile and maximise the DRPR. The burden in using GA has to do with the tuning of parameters such as selection, mutation, crossover and the number of generations in order to ensure convergence with this kind of problem. This was a MIP. The tuning was done manually with several runs. This was to check if there will be a significant change in the final values obtained for the fitness function. The final values for scenarios 1 and 2 are given in Table 4. The computational time is dependent on the number of variables and also the maximum number of generations.

The inductive mode of operation of IBDGs during steady state as observed in scenario 2 had a significant impact on IBDGs and CAPs location and sizing. The amount of reactive power absorbed by the IBDGs during steady was 17 MVAr in scenario 2, this partially accounted for the increased losses as compared with scenario 1. Also, the introduction of the third objective function in scenario 2 will reduce the weights assigned to the objective functions as compared with scenario 1. Consequently, it is sacrificing the two steady state objective functions (losses and voltage profile improvement) as shown in Tables 2 and 3. The losses and voltage profile index were higher in scenario 2 as compared in scenario 1. However, individual analysis for each bus shows that the voltage profile for eight out of the 15 buses was improved in scenario 2 with respect to scenario 1 as shown in Fig. 5. The transient response of the voltage in response to three phase-to-ground faults justifies the need in forfeiting these steady state objective functions. A higher penetration level of DGs continues to be the main reason behind the introduction of ANMSs in DNs. The proposed scheme, scenario 2, resulted in the 25.56%
increase penetration level of renewable energy DG, IBDGs. The IBDGs total capacity was 56 MVA as compared with scenario 1, which was 44.6 MVA. Thus, it demonstrates the effectiveness of the ANMS in a steady state system optimisation.

4.2 Dynamic RPR

Studies on VSM indicate a correlation with DRPR. This was a major cause of the blackout in North America in 2003 [46]. Maximising DRPRs will significantly improve the voltage stability of the network. The performance of this ANMS in using DGs to maximising the DRPR is determined by the PQ chart developed based on the optimisation results of scenario 2 as shown in Fig. 6. The chart was developed by varying the active power flow ($P$) from the IBDGs and determining the corresponding $Q$ through optimised load flow results. Fig. 6 shows the reactive power capability of IBDGs within the PF constraint as indicated in red. The $Q$ points are optimal operating points of the IBDGs shown in blue. The shaded portion between the lagging PF limit and the $Q$ operating points is the available DRPR that can be utilised by the DN during system contingencies. As the active power ($P$) increases, the DRPR also increases because of the limitations imposed by the PF constraints. Even though this scheme is to allow the IBDGs to operate in an inductive mode of operation, Fig. 6 indicates the DG operating in lagging mode for IBDGs located at buses 5 and 10 during low active power levels.

Although the one located at bus 2 always operated in leading mode. The operating point of the IBDG at a bus coincided with the capacitive limit. These results further demonstrate that the location of IBDGs and the capacity will significantly affect their mode of operation whether they operate in lagging or leading mode for optimal conditions in the network.

4.3 Performance in response to system disturbances

The proposed optimised control strategy aims to maximise the DRPR to enhance the transient response of the DN.

4.3.1 Performance in response to three phase-to-ground fault: To demonstrate the transient response, a three-phase-to-ground fault was applied at the bus 5 at 5 s and lasted for 150 ms for the two reported scenarios. The transient response is evaluated based on the recovery time after clearing the fault. Fig. 7 shows the voltage response of some selected buses in both cases. After the fault, it took $\sim 130$ ms for the voltage to get to 0.9 pu for scenario 2 while scenario 1 was 160 ms at bus 5. The difference in response time ($\Delta t$) for buses 10, 11, and 12 were $\sim 90, 85$ and $\sim 100$ ms, respectively. The amount of reactive power supplied by each IBDG in scenario 2 and substation compared with scenario 1 is shown in Fig. 8. During the fault, the substation supplied $\sim 200$ MVAr, which was significantly high in scenario 1 as shown in Fig. 8(a). This might cause damage to the substation transformer and other sensitive devices on the network due to overloading. In scenario 2, the reactive power supplied was about 50 MVA, thus reducing the stress being made on the transmission network.

The reactive power supplied by each IBDG is also shown in Fig. 8(b). IBDG at bus 2 delivered a higher amount of $Q$ as compared with the other IBDGs. At bus 10, the IBDG is operated in a less inductive mode. Since supplying reactive power would have resulted in the voltage at the bus thus exceeding the maximum permissible voltage immediately after the clearance of the fault.

4.3.2 Transient performance with dynamic load: To further demonstrate the effectiveness of the ANMS, 35% dynamic loads are introduced into the network. A three-phase-to-ground fault was applied at bus 5 at 5 s for 100 and 150 ms, respectively. Results from Fig. 9 show the performances of some selected buses. The difference in response time ($\Delta t$) between the two scenarios for bus 5 was about 200 ms. The other buses exhibited a similar trend with

| Table 3 Summary results of scenario 2 |
|-------------------------------------|
| Bus location | DG Size, MVA | $P$, MW | $Q$, MVAr | Bus location | CAP bank Size, MVA | TAP setting OLTC | VR | Substation $P$, MW | Substation $Q$, MVAr | Losses $V_p$ |
| 2          | 22.8          | 21.7    | $-7.1$   | 3           | 1.8          | 0.95 | 0.95 | 0.37           | 20.39       | 0.865 | 1.47 | 0.097 |
| 5          | 22.5          | 21.4    | $-7.0$   | 5           | 2.0          | -     | -     | -              | -          | -     | -     | -     |
| 10         | 10.7          | 10.2    | $-3.3$   | 6           | 2.2          | -     | -     | -              | -          | -     | -     | -     |
| 10         | 2.0           | -       | -        | -           | -            | -     | -     | -              | -          | -     | -     | -     |

| Table 4 Final fitness function values |
|-------------------------------------|
| scenario 1 | 0.23121         |
| scenario 2 | $-4.85509$       |

Fig. 5 Voltage profiles of buses for both cases

Fig. 6 (a)–(c) PQ chart of IBDGs at buses 10, 2 and 5, respectively

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scenario 2 demonstrating enhanced transient’s response as compared with scenario 1. When the fault durations were increased to 150 ms, the proposed scheme, scenario 2, still continued to show a better transient response as compared with scenario 1 as shown in Fig. 10 for some selected buses, thus demonstrating the effectiveness of the scheme.

Finally, the proposed planning optimisation algorithm to optimally locate and size the IBDGs and CAPs for improving the steady state and transient performance of the 16 bus UKGDS has been verified. The proposed optimisation algorithm included the IBDGs, CAP banks, OLTC position and voltage regulators’ settings to achieve the optimal operation at peak and off-peak loads for the aim of enhancing the voltage transient stability as well as steady state performance based on the ANMS. The presented work emphasises the optimal locations based on the steady state performance such as enhancing voltage profile and minimising system losses and also transient performance such as maximising the DRPR, leading to improved voltage stability performance with maximum DG penetration. In addition to that, an online DRPR monitoring for IBDGs is introduced to assess capability for supporting the electric grid at different loading conditions.

5 Conclusion

In this study, an ANMS, which involves a multi-objective optimisation method of allocation and sizing IBDGs and CAPs’ bank, was carried out. The optimisation took into consideration OLTCs, voltage regulators, CAPs’ bank and IBDGs to achieve the voltage regulations within a range of 0.94–1.06 pu during steady state and also improving the transient response during disturbances such as grid fault. It was based on the three objective functions: (i) improving voltage profile of the DN, (ii) minimising system losses and (iii) maximising the DRPR improves the transient response and stability margin of the system. In addition, the proposed scheme allows higher integration of renewable energy DG, 25.56% increase of IBDGs penetration. The optimisation results implemented in PSCAD/EMTDC vividly demonstrated the improvement in the transient response during a three-phase to ground fault. This performance was achieved for both static and dynamic load conditions on the system for various fault durations. While DGs operate in an inductive mode, some negative effects were encountered in increased losses as compared with the conventional DGs’ operation. However, the main advantage of the proposed scheme has been clearly demonstrated in this study.

6 References

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7 Appendix

PV module parameters are shown in Table 5.

| PV module parameters | electron charge | shunt resistance | ideality factor | STC short circuit current | STC temperature | Boltzmann constant $e$  |
|----------------------|-----------------|-----------------|----------------|--------------------------|----------------|-------------------------|
| $q$                  | $1.6 \times 10^{-19}$ |                  |                | $R_{sh} = 1000 \Omega$ |                | $k = 1.38 \times 10^{-23}$ J/K |
| $R_{sh}$             |                  |                  |                | $A = 1.5$            |                | $T_{ref} = 298 K$         |
| $T_{ref}$            |                  |                  |                | $I_{sc} = 2.5 A$     |                | $k = 1.38 \times 10^{-23}$ J/K |
| $I_{STC}$            |                  |                  |                | $T_{ref} = 298 K$    |                | $T_{ref} = 298 K$         |
| $V_{oc}$             |                  |                  |                | $R_{in} = 0.02 \Omega$ |                | $T_{ref} = 298 K$         |
| $S_{Sol}$            |                  |                  |                | $STC$               |                | $T_{ref} = 298 K$         |

Table 5 PV module parameters