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A Fault Level-Based System to Control Voltage and Enhance Power Factor Through an On-Load Tap Changer and Distributed Generators

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ABSTRACT The on-load tap changer is critical for voltage regulation, however, its voltage regulation philosophy is suitable for one-directional power flow power systems. Since distributed generators introduce bidirectional power flow, the conventional operation of the on-load tap changer will be highly impacted, resulting in high voltage magnitudes that exceed acceptable limits, frequent voltage magnitude fluctuations, and the increase in overall reactive power supply when distributed generators start absorbing/injecting reactive power. Therefore, an adaptive control system is proposed on this paper that alters the existing voltage regulation philosophy of the on-load tap changer and also coordinate the voltage regulation capabilities of distributed generators with those of the on-load tap changer for optimal overall voltage regulation and the reduction of reactive power that flows through the power system, enhancing the power factor thereof. The proposed control system will change the centralized, and single-variable busbar voltage monitoring technique of the conventional philosophy with a decentralized, and multi-variable strategy that controls voltage based on the average voltage of the entire distribution network. The control system will calculate the on-load tap changer and distributed generators setpoints based on the overall average network voltage, average voltage deviation from nominal voltage, generators points of connection voltage and the total reactive power that flows through the power transformer. The control system was tested on a 22kV network modelled in MATLAB SIMULINK and the results attained revealed that the proposed multi-stage control system can successfully control voltage and simultaneously improve power factor.

INDEX TERMS Active power, distributed generation, fault level, on-load tap changer, power distribution network, power factor, reactive power, voltage regulation.

I. INTRODUCTION

Voltage regulation is a critical criterion of any power system. Through voltage regulation, the power system can provide minimal voltage magnitude variation as the load on the power system changes with time [1]. In power distribution networks, voltage regulation is achieved using an on-load tap changer (OLTC) that is integrated into the high voltage windings of the power transformer [2]–[4]. Since the OLTC is positioned at the substation, it keeps voltage magnitudes well regulated by maintaining a fixed substation busbar voltage magnitude in accordance with a predetermined and fixed OLTC reference voltage [5]. Keeping the substation voltage magnitude fixed is effective in passive power distribution networks with no distributed generators (DGs) connected, since a passive power distribution network always has its highest voltage magnitude at the substation. However, the centralized voltage regulation strategy of the OLTC is negatively impacted by the connection of DGs on the power distribution network. This is because the excessive reverse power flow creates a network in which the substation busbar is not the location of highest voltage magnitude anymore. Since the conventional OLTC voltage regulation philosophy's effectiveness is dependent on substation voltage being the highest, the results when DGs are connected will be large voltage magnitudes variations and high voltage magnitudes [6]–[8]. This makes the power distribution network voltage magnitudes very difficult to control when DGs are connected [9].

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Reverse power flow is the main cause of high voltage magnitudes, as the DG generation start to exceed the feeder load, voltage start to rise excessively [10]. On the other hand, voltage variations are caused by the intermittent nature of DGs since the active power generation of most DGs is linked to weather. High voltage magnitudes and variation in voltage magnitudes impact the network reliability as millions of devices connected to the power system operate efficiently when voltage is regulated within acceptable limits. Since the conventional OLTC voltage regulation philosophy cannot curb high voltage magnitudes or constraint voltage fluctuations caused by DGs, It is therefore critical that an effective and decentralized voltage regulation strategy be introduced to deal with an active power distribution network that has numerous DGs connected to it.

Voltage regulation strategies that aims to improve the voltage regulation philosophy when DGs are connected have been proposed in literature. However, literature also shows that some of these strategies improve voltage regulation while reducing the power system power factor [11].

In [12], a method is proposed that combines the voltage magnitudes of feeders and the active power generated by a solar plant to compute the required OLTC tap position on an hourly basis. The setpoint/OLTC tap position is calculated every hour in relation to the distribution network voltage magnitudes and the solar plant active power generation. Simultaneously, the solar plant also uses reactive power capability to keep a constant voltage magnitude at its point of connection (POC).

In [13], a strategy is proposed that uses the fast response of DGs to prevent excessive voltage variations on feeders and hence prevent OLTC excessive operation. The DGs uses reactive power capability to limit any surge or dip in voltage magnitudes within the feeder. The strategy also uses capacitor banks to satisfy the long-term reactive power demands of the feeder while using the conventional OLTC voltage regulation strategy.

In [14], a strategy is proposed that uses a ranking algorithm to control DG reactive power, controllable loads and the OLTC to alleviate undervoltage and overvoltage conditions when detected on the network. In [15], a strategy is proposed that uses a fuzzy logic controller and state estimation to control the OLTC and solar plant for voltage regulation. When the minimum and maximum voltage magnitudes are too further apart, the OLTC is locked and the solar plant utilizes reactive power to control voltage. The OLTC is instructed to regulate voltage when the minimum and maximum voltage magnitudes are closer to each other. In [16], a strategy is proposed that improves the power system secondary voltage control technique by incorporating a compressive sensing methodology that improves data transmission for optimal real time voltage regulation. This ensures that the power system respond quickly and regulate bus voltages as the intermittent DGs causes voltage fluctuations.

In [17], a strategy is proposed that controls the OLTC tap position to keep the maximum measured voltage and the minimum measured voltage within defined maximum and minimum voltage limits. The OLTC will start changing tap position if the minimum or maximum voltage is outside the defined limits, the OLTC would stop when it has successfully brought voltage magnitudes within defined limits or has reached maximum tap position.

In [18], a strategy is proposed that coordinate the OLTC and capacitor banks based on the rolling optimisation algorithm, and also control the soft open point devices based on the multi-objective optimization model. The purpose of the methodology is to prevent voltage fluctuations when DGs are connected.

In [19], a strategy is proposed that uses a PI controller to control the active power generated by solar plants in medium and high voltage networks and also control the reactive power of solar plants in low voltage networks to prevent voltage fluctuations. The OLTC is used as back up when the PI controller fails to efficiently regulate voltage magnitudes. In [20], a strategy is introduced that coordinate the OLTC, static voltage regulator, shunt capacitors and energy storage systems. These devices would regulate voltage magnitudes based on a sequence that is dependent on the time of day and the feeder loading.

In [21], a strategy is proposed that coordinate DGs, OLTC, and capacitors using the SCADA (Supervisory Control and Data Acquisition) system to collect remote voltage magnitudes. The strategy then uses micro genetic algorithm on the first stage to determine the OLTC tap position and then use the recursive genetic algorithm to calculate the setpoints of all reactive power devices on the power network. In [22], a strategy is proposed that coordinate an electronic tap changer and distributed generators for voltage regulation. However, the high cost of electronic tap changers limit their usage [23]. In [24], a strategy is proposed that uses a genetic algorithm to coordinate different voltage regulation equipment on the distribution network including OLTC, shunt capacitors, static var compensator and step voltage regulator. However, the strategy in [24] did not utilize reactive power from DGs to further improve the voltage regulation process nor implement a power factor correction strategy.

While the techniques proposed in [12]–[24] successfully achieves voltage regulation, they use different algorithms to search for a single voltage magnitude that will be used to determine the statuses of voltage regulation equipment. This single voltage magnitude might be a fixed voltage magnitude, maximum voltage magnitude, or the minimum voltage measured within the power network or estimated through state estimation. In addition, none of the strategies proposed in [12]–[24] coordinate the voltage regulation devices such that they achieve both voltage regulation and power factor enhancement.

Therefore, the strategy proposed on this paper will change the conventional operation of the OLTC that focuses on keeping a fixed substation voltage and that suggested in multiple literature of selecting a voltage magnitude that the OLTC must focus on. Instead, the overall network average voltage will be used to determine the OLTC setpoint/reference voltage magnitude. Voltage magnitudes of locations where DGs are connected on the power distribution network and voltage magnitudes in locations with the highest and lowest fault levels in each feeder will be measured. Using all these measured voltage magnitudes, a single average network voltage magnitude and the overall average voltage deviation from nominal voltage will be computed. Initially, DGs will use voltage magnitudes measured where they are connected and dispatch reactive power accordingly in relation to the relationship between voltage and reactive power where they are located. Thereafter, based on the computed single average network voltage and the average voltage deviation, the OLTC reference voltage will be determined. If the average voltage deviation from nominal voltage is a positive value, the control system will calculate the OLTC reference voltage to be below nominal voltage to reduce the average network voltage magnitude. If the average voltage deviation from nominal voltage is a negative value, the control system will calculate the OLTC reference voltage to be above nominal voltage to boost the average network voltage magnitude.

Therefore, once the reference voltage is computed, the OLTC will always try to equalize the calculated reference voltage with the measured voltage at the substation busbar in real time. Furthermore, as the voltage magnitudes of the power distribution network changes because of DGs and the OLTC action, DGs will utilise their remaining reactive power capability to improve the power system power factor. The control system will calculate all variables required for optimal voltage control and power factor enhancement in real time. Since the control system uses existing power system equipment, and most power distribution networks have existing communication systems to monitor reclosers, the cost of implementing the control system will below.

Literature also show that the transmission network, the medium voltage, and the low voltage distribution networks have different resistance and reactance values and hence affected differently by the connection of DGs [25]. Therefore, the control system proposed on this paper will evaluate and improve voltage regulation on a medium voltage power distribution network with high penetration of DGs. In addition, the designed control system can operate with any type of DG that has reactive power capability. This is because technology has advanced, and most DGs have reactive power capability as enforced by different grid connection codes [26], [43].

This paper will present the following contributions:

- Improve voltage regulation by introducing a new OLTC voltage regulation philosophy that is based on power distribution network average voltage deviation from nominal voltage and fault levels.
- Coordinate the new OLTC voltage regulation philosophy with the DG reactive power voltage regulation philosophy based on time delay for optimal power system voltage regulation.
- Coordinate both the newly introduced OLTC voltage regulation philosophy and DGs for reactive power compensation and power system power factor improvement.
- Allow the connection of more DGs without exceeding the network prescribed voltage magnitude limits.

The arrangement of this paper will be as follows; the introduction was highlighted in section I, section II will explore the technical operation of the OLTC and DGs in voltage control, section III will introduce the control system, section IV will present the results attained and their analysis when the control system was tested and section V will give conclusions.

II. OLTC CONVENTIONAL VOLTAGE CONTROL PHILOSOPHY, DGs AND THE POWER FACTOR

A. OLTC CONVENTIONAL OPERATION

Voltage regulation in power distribution networks is achieved through many equipment, however, the OLTC is the most common and effective. The effectiveness of the OLTC originate from its ability to regulate the voltage of multiple feeders by keeping the secondary voltage of the Power transformer constant as the load varies [27]. Therefore, as the network load changes, the OLTC keeps the transformer secondary voltage/busbar voltage constant by altering the transformer winding ratio [28]. Figure 1 shows the operation of the OLTC while maintaining a fixed busbar voltage and Figure 2 shows the operation of the OLTC while operating using LDC (Line Drop Compensation) where it estimates a remote location voltage and maintain the estimated voltage at a fixed voltage magnitude [29].

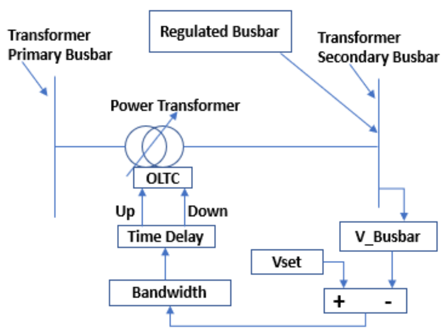

FIGURE 1. Conventional OLTC operation based on fixed busbar voltage [29].

A transformer with an OLTC can be defined by the equation 1 where V_2 is the transformer secondary voltage, V_1 is the transformer primary voltage, a is the adjustable transformer ratio, I_2 is the transformer secondary current and $Z_T(a)$ is the transformer impedance [30].

$$V_2 = \frac{V_1}{a} - Z_T(a)I_2 \tag{1}$$

Since the transformer ratio a in equation 1 is a non-constant variable that depends on the OLTC tap position, it is therefore represented by equation 2 where a_0 is the transformer rated winding ratio, Δa is the number of steps the OLTC has moved

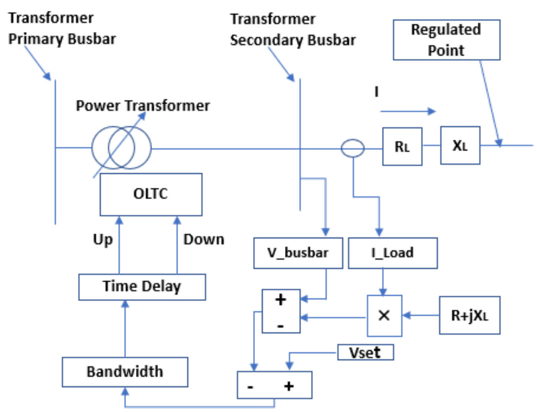

FIGURE 2. **Conventional OLTC operation based on fixed remote voltage [29].**

and n is the tap position in which the OLTC has settled on [29]

$$a = a_0 + n\Delta a \tag{2}$$

According to equations 1 and 2, an OLTC can alter the transformer secondary voltage V_2 by changing the transformer winding ratio a. The target value of the secondary voltage V_2 is determined based on the measured busbar voltage and a predetermined set voltage as illustrated in Figure 1.

Therefore, the OLTC will always strive to keep the secondary transformer voltage V_2 equal to a fixed set voltage magnitude V_{set}. However, monitoring only the substation busbar voltage and keeping it at a fixed voltage makes the technique static and unable to respond effectively to rising and fluctuating voltage magnitudes that distributed generators will introduce when connected [29]. Power transformers with OLTC can also alter turns ratio to control a remote voltage magnitude instead of busbar voltage as shown in Figure 2.

The OLTC estimate voltage at a regulated point far from the substation based on the current that flows through the transformer and the line impedance from the transformer to the regulated location. Voltage at the regulated point (RP) is estimated by means of equation 3 where V_{RP} is the estimated voltage at the regulated point, V_{Busbar} is the transformer secondary voltage, I_{Load} is the load current, R_L is the line resistance, X_L is the line reactance and ϕ is the power factor angle [29].

$$V_{RP} = V_{Busbar} - I_{Load}(R_L cos\phi + X_L Sin\phi) \tag{3}$$

After estimating the voltage magnitude at the regulated point, the OLTC will then alter its tap position to ensure that voltage at the regulated point is equivalent to the predetermined and fixed voltage set point. However, estimating voltage at a remote location depends on load current and the power factor as shown in equation 3. Since these parameters are impacted when DGs are connected as discussed in subsections B and C, the OLTC method of voltage regulation based on a remote location is also affected. In addition, since the method still uses a fixed OLTC reference voltage, it cannot adapt to deal with voltage challenges introduced by DGs.

B. DGs AND VOLTAGE REGULATION

The introduction of high active power generation by DGs to a power distribution system create several challenges, these challenges include voltage magnitudes increasing above satisfactory limits, recurrent voltage variations and reverse power flow [32]–[36]. The impact can be demonstrated using equations 4-6 where ΔV is the difference in voltage between two points, R is resistance of the line, P_L is the active power drawn by the load of the network, Q_L is the reactive power load of the network, X is reactance of the line, V_{OLTC} is the substation busbar voltage, V_G is the generator terminal voltage, Q_G is the reactive power output of the DG, and P_G is the active power generation of the DG [23], [37].

Equations 4 and 5 represent a network with no DGs connected. The network voltage can be effectively regulated using conventional OLTC method of a fixed reference voltage magnitude since there is no reverse power flow, frequent voltage fluctuations and high voltage magnitudes and the substation busbar voltage V_{OLTC} will permanently be the peak voltage magnitude on the network.

$$\Delta V = \frac{R.P_L + XQ_L}{V_{OLTC}} + j\frac{X.P_L - R.Q_L}{V_{OLTC}} \tag{4}$$

Since imaginary term is very small, equation 4 can be simplified to equation 5.

$$\Delta V \approx \frac{R.P_L + XQ_L}{V_{OLTC}} \tag{5}$$

Equation 6 represent a power distribution network with DGs connected. Since the change in voltage ΔV is dependent on DG generation P_G, the change in voltage will fluctuate frequently as the DG generation fluctuate with changing weather pattern. In addition, the substation busbar will not permanently have the peak voltage magnitude. The peak voltage magnitude will shift from one point to the other as the difference between DG generation P_G and network load P_L changes. It is these reasons that renders the static conventional OLTC voltage regulation philosophy that relies on a fixed voltage magnitude for voltage regulation ineffective when DGs are connected.

$$\Delta V \approx \frac{R.(P_G - P_L) + X(Q_G - Q_L)}{V_G} \tag{6}$$

A voltage regulation philosophy is therefore required that will not use a fixed OLTC reference voltage but change the OLTC reference voltage as the network voltage magnitudes are influenced up and down by DGs.

C. DGs AND THE POWER FACTOR

Most grid connection codes for distributed generators including the South African grid code for renewable energy plants now requires DGs to have reactive power capability for voltage control purposes. Therefore, DGs can absorb reactive power to reduce voltage or inject reactive power to increase voltage magnitudes. The absorption and injection of reactive power by DGs will affect the power system power factor [10]. The power factor is computed based on the amount of active and reactive power that flows through the power system as shown in equation 7 where $Cos\ \phi$ is the power factor, P is active power, S is apparent power, and Q is reactive power [37].

$$Cos\phi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{7}$$

According to equation 7, a power system that has high magnitude of reactive power will have a low power factor. The consequences of a low power factor on the power system include high power losses and poor voltage regulation [37], [38]. It is because of this reason that power system engineers places reactive power compensation equipment in locations with high reactive power demand to guarantee that reactive power needed is supplied closer to the point of demand and does not flow long distances through the power system. Since DGs can utilise reactive power to control voltage, they will increase the network reactive power demand and therefore lowers the power factor. Therefore, a reactive power compensation technique will be embedded into the control system to ensure optimal power system operation.

III. PROBLEM FORMULATION

The introduction of distributed generation using renewable energy sources has introduced multiple challenges to the power system which include intensified voltage magnitudes, voltage fluctuations, and bidirectional power flow. The conventional OLTC voltage regulation philosophy that uses a fixed voltage magnitude was designed for a one-directional power flow power system with the voltage magnitude highest at the substation busbar. Therefore, distributed generation makes the OLTC voltage regulation philosophy ineffective. In addition, distributed generators also affect the power system power factor as they absorb and inject reactive power for voltage control. Although algorithms exist that can determine the DG optimal location and size for minimal impact on the power distribution network [41], [42]. The majority of DGs are still connected to the power system without the implementation of optimal location and size algorithms. As a result, these DGs will have severe and negative side effects on the power distribution network operation. Therefore, a new voltage regulation philosophy is designed on this paper that will control voltage when DGs are connected anywhere on the medium voltage power distribution network. The proposed control strategy will calculate the OLTC reference voltage based on a computed average network voltage instead of using a fixed OLTC reference voltage. Since the OLTC reference voltage is calculated based on the average network voltage, and the average network voltage is computed using voltage magnitudes obtained throughout the power distribution network, the OLTC reference voltage will change as power distribution network voltage magnitudes are influenced by distributed generation. Therefore, the control system will always calculate an optimal OLTC reference voltage that minimizes voltage deviations within the medium voltage power distribution network.

The control system will also control the reactive power output of distributed generators based on the voltage magnitude at their points of connection. To prevent conflict between DGs and the OLTC, the control system will enable DGs first for voltage regulation while it places the OLTC on time delay. If DGs cannot successfully regulate network voltage, the control system will issue new optimal voltage setpoints to the OLTC and the OLTC will act when the time delay has elapsed. In addition, the proposed control system will also enhance the power system power factor that is reduced as DGs export and import reactive power. Therefore, the proposed control system controls the individual DGs and the OLTC for optimal voltage regulation and effective power factor enhancement.

A. OBJECTIVE

The objective of the philosophy introduced in this paper is portrayed using equations 8-10 where f is the objective function, a is a measured location, V_{avg} is the overall network average voltage, V_n is the nominal voltage, P_{Gi} and P_{Li} are the generated and load active power, Q_{Gi} and Q_{Li} are the generated and consumed reactive power, V_i and V_k are any two buses in which power flows between, G_{ik} and B_{ik} are parts of the Y bus matrix and δ is the voltage angle difference between bus i and k.

$$f = min|\left(\sum\nolimits_{a=1}^{N}\left(V_{avg}\right) - V_n\right)| + max(\frac{P}{\sqrt{P^2+Q^2}}) \tag{8}$$

$$\text{s.t } P_{Gi} - P_{Li} - V_i \sum\nolimits_{k=1}^{n} V_k\ (G_{ik}cos\delta_{ik} + B_{ik}sin\delta_{ik}) = 0 \tag{9}$$

$$Q_{Gi} - Q_{Li} - V_i \sum\nolimits_{k=1}^{n} V_k\ (G_{ik}sin\delta_{ik} - B_{ik}cos\delta_{ik}) = 0 \tag{10}$$

As depicted in equation 8, the strategy proposed in this paper will utilise both the OLTC and DGs to prevent the overall average network voltage from drifting away from nominal voltage. This will ensure that power distribution network voltage regulation is not based on a single point voltage or a fixed voltage magnitude but the overall network voltage. In addition, the OLTC and DGs will be further coordinated to prevent the power factor from drifting too far from unity. Therefore, equation 8 shows the design objectives of the control system which are minimizing voltage deviation and maximizing power factor. The power factor variables P and Q in equation 8 will be measured at the substation. Equations 9-10 are the power system load flow equations [11], [44].

B. PROPOSED OLTC-DG VOLTAGE REGULATION AND POWER FACTOR ADVANCEMENT CONTROL SYSTEM

The control system will require several voltage magnitudes throughout the network to be able to compute the average network voltage. To get an accurate overall network average voltage, locations with the possibility of having the highest and the lowest voltage magnitudes will need to be measured. A common practice would be to assume that the end of feeders are locations of lowest voltage magnitudes on a power network. However, since power distribution networks spread out in a tree-like structure, it is difficult to determine the end of a feeder. In addition, even if the end of a feeder is identified, it might not be the location of lowest voltage since some power distribution networks can have multiple conductor types in one feeder. Therefore, three voltage magnitudes will be measured in each feeder on this control system, which are; the location with the highest fault level (V_{fault_High}), the location of lowest fault level (V_{fault_low}) and the connection points of all DGs ($V_{DG}(n)$).

The three locations will be measured for every feeder that is part of the medium voltage power distribution network. Based on all measured voltage magnitudes, the control system will use equation 11 to determine the OLTC busbar reference voltage where V_{OLTC_Ref} is the OLTC reference voltage, V_a is the measured voltage and N is the number of locations that have had their voltage magnitudes measured. Equation 11 is used to compute the average network voltage magnitude and the OLTC reference voltage based on all measured voltage magnitudes V_a. In addition, equation 11 will operate in real time where voltage magnitudes are measured and sent through the SCADA system.

$$V_{OLTC\_ref} = \sum\nolimits_{a=1}^{N} \frac{V_n - V_a}{N} + V_n \quad (11)$$

The OLTC will therefore always keep the transformer secondary voltage at V_{OLTC_ref} with a tolerance of $\pm V_{error}$.

The voltage V_{OLTC_ref} will change as the network conditions change; therefore, the OLTC will regulate voltage based on real time network conditions. Rising voltage magnitudes due to DGs will also affect the voltage V_{OLTC_ref}, therefore, the OLTC will also respond accordingly and curb the rising voltage magnitude. Since the OLTC is operated by mechanical switches, it is slow in operation. Therefore, the control system will enable DGs first in voltage regulation. The magnitude of reactive power each DG will be required to import/export will be calculated based in equation 12 where *QDG_V(n)* is the reactive power required to regulate voltage, $V_{DG(n)}$ is the DG POC voltage and S_{VQ} is the sensitivity of voltage to reactive power at the DG POC. The term S_{VQ} is the ratio between a voltage change of 0.1p.u and the reactive power required to cause a 0.1p.u change in voltage at the DG POC.

$$QDG\_V(n) = \frac{V_n - V_{DG(n)}}{S_{VQ}} \quad (12)$$

In addition to reactive power desired from DGs to control voltage, the system will further compute the amount of reactive power available for power factor correction in each DG based on equations 13-14. The maximum reactive power desired to control the power factor from each DG will be determined with respect to the total reactive power that passes through the substation transformer and the number of DGs involved in power factor advancement as shown in equation 15. The control system will then compare the magnitude of reactive power attained between equations 13 or 14 and equation 15 and use the minimum value. In addition, DGs will only participate in reactive power compensation for power factor advancement if voltage at their POC is between *Vmin* and *Vmax*. Furthermore, only DGs that have used less than 50% of their rated reactive power in voltage regulation will be chosen for power factor enhancement by the control system. This is because DGs that imports/exports high magnitude of reactive power indicate voltage problems where they are connected, and hence using these DGs for power factor enhancement will worsen the voltage problem. Therefore, as the OLTC changes the overall average network voltage, DGs will simultaneously adjust their reactive power to prevent the power factor from dropping significantly.

The reactive power each DG must dispatch for power factor advancement will be determined based on equations 13-15 where *QDG_PF(n)* is the reactive power available for power factor advancement, *Vmax* is the maximum defined voltage, *Vmin* is the minimum defined voltage, $Q_{Measured}$ is the reactive power flowing through the substation transformer, x is the number of DGs involved in power factor advancement and QDG_PF_{MAX} is the maximum reactive power required from each DG for power factor enhancement. Equation 16 shows the total reactive power a DG will export/import for both voltage control and power factor enhancement where $Q(n)$ is the total reactive power a DG involved in power factor enhancement must import/export for both voltage regulation and power factor correction.

$$QDG\_PF(n) = \frac{V_{max} - V_{DG(n)}}{S_{VQ}} \quad \text{for } Q_{\text{Measured}} < 0 \quad (13)$$

$$QDG\_PF(n) = \frac{V_{DG(n)} - V_{min}}{S_{VQ}} \quad \text{for } Q_{\text{Measured}} > 0 \quad (14)$$

$$QDG\_PF_{MAX} = \frac{Q_{Measured}}{x} \quad (15)$$

$$Q(n) = QDG\_V(n) + min(QDG\_PF(n), QDG\_PF_{MAX}) \quad (16)$$

Equation 13 shows that the amount of reactive power available to a DG for power factor improvement will be based on the difference between the predefined maximum voltage *Vmax* and the POC voltage. When the POC voltage is equal or greater than the predefined maximum voltage *Vmax*, the DG will not use reactive power to control the power factor. In addition, the control system will allocate more reactive power for power factor control if the DG POC voltage is further from *Vmax* and allocate low reactive power if the POC voltage is closer to *Vmax*. Equation 14 shows the same effect for voltage magnitudes below or equal to the predefined minimum voltage *Vmin*.

Figure 3 shows a flow chart of the control system. The flow chart of Figure 3 is also explained in steps 1-5 as follows.

Step 1: Voltage magnitudes of multiple sites on the power distribution network will be measured. These sites will be the connection points of DGs and locations of highest and lowest fault levels on each feeder. In addition, the system

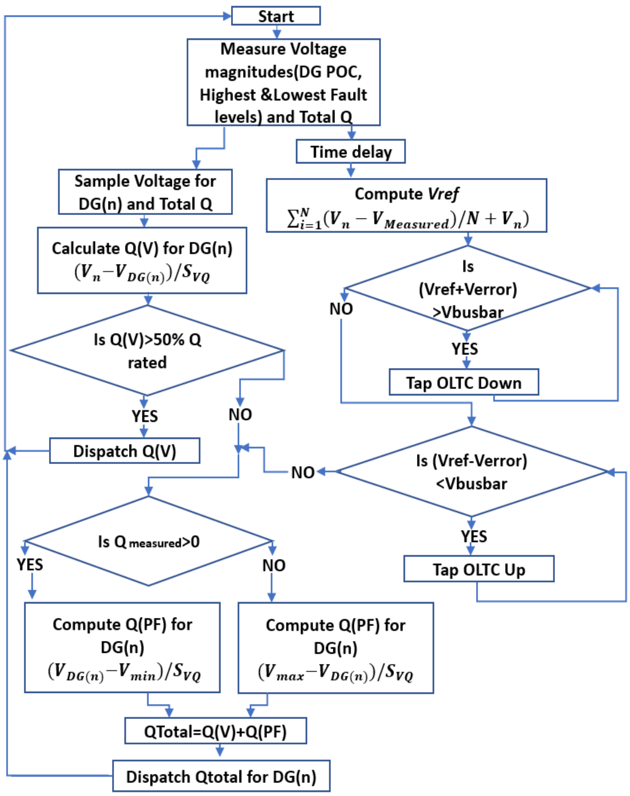

FIGURE 3. Proposed Control Algorithm.

will measure reactive power flowing through the substation transformer.

Step 2: The system will utilise equation 12 for each DG to determine if the respective DG need to provide reactive power for voltage regulation and the magnitude of reactive power required based on the measured voltage at the respective DG POC. If equation 12 returns a zero value, there is no voltage regulation required. Any other value indicate that voltage regulation is required, and the returned value is the amount of reactive power required to control voltage. Simultaneously, the system will put the OLTC on time delay.

Step 3: The system will then compare the value returned by equation 12 for each DG with the respective DG's reactive power capacity. If the value returned by equation 12 is greater than 50% of the DG's reactive power capacity, that respective DG immediately export/import that reactive power. If the value is less than 50% of the DG's reactive power capacity, the control system takes the DG to the power factor enhancement stage.

Step 4: The system assesses the reactive power flowing through the substation transformer to determine if it is greater or less than zero. If it is less than zero, the system uses equation 13 to determine the reactive power required for each DG to enhance power factor, if it is greater than zero, the system uses equation 14. The system will then combine the reactive power required for voltage regulation and that required for power factor enhancement and instruct DGs to import/export.

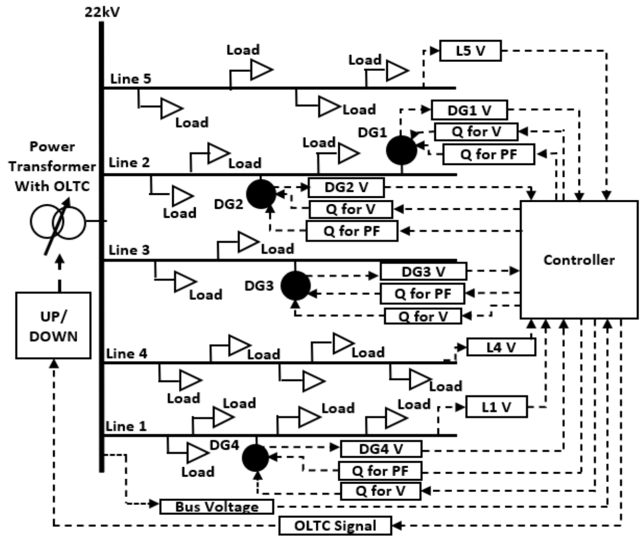

FIGURE 4. Simplified medium voltage power distribution network with five feeders and four DGs.

Step 5: Once the time delay has elapsed, the system will then calculate the OLTC reference voltage based on the overall average network voltage deviation from nominal voltage. Once the OLTC reference voltage has been computed, the control system will compare the computed reference voltage and the substation busbar voltage and then change the OLTC tap position until the reference voltage and the substation busbar voltage are matched. Since this process is real time and continuous, the control system will constantly adjust the DGs output reactive power to enhance the power factor as the OLTC adjust its tap settings concurrently.

IV. RESULTS AND ANALYSIS

To evaluate the effectiveness of the control system, a South African 22kV medium voltage power distribution network is used. The power distribution network consists of a 40MVA, 132/22kV power transformer equipped with an OLTC. The transformer supplies five overhead 22kV lines simultaneously through a common 22kV busbar. DGs were then added to the 22kV network as portrayed in Figures 4 and 5. Since DGs can be connected anywhere on the medium voltage power distribution network during application, the location of DGs on this paper was chosen to represent all possible scenarios. Therefore, DGs were distributed on locations with high, medium, and low fault levels on the 22kV network. These locations were chosen since they have different network strength and hence affected differently by DGs. In addition, the number, and sizes of DGs was chosen such that they create a reverse power flow scenario and high voltage magnitudes since the control system was designed to alleviate increased voltage magnitudes caused by DGs.

Figure 4 illustrate a simplified medium voltage power distribution network in which one substation with an OLTC equipped power transformer supplies five 22kV lines. Four DGs were also connected to feeders 1, 2, and 3. The actual

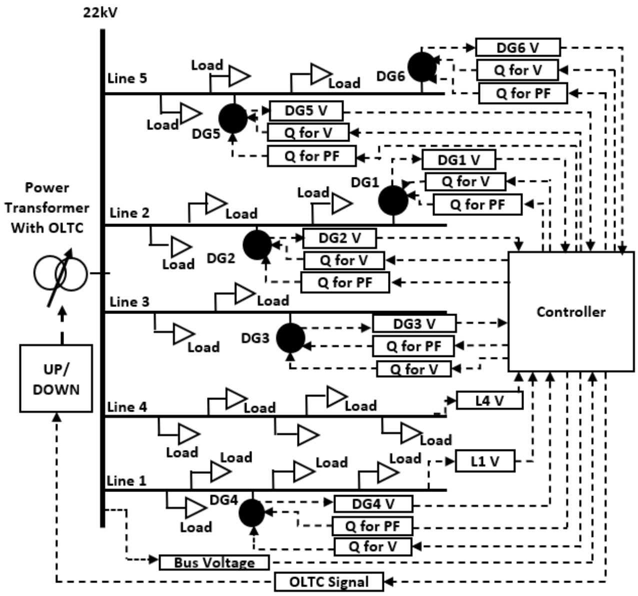

FIGURE 5. Simplified medium voltage power distribution network with five feeders and six DGs.

TABLE 1. Lowest/Highest fault levels, length and loading per feeder.

Feeder	Fault Level(A)	Feeder Load (MW)	Feeder Length (km)
Feeder 1 (L1)	917.8 - Lowest	9.30	15
Feeder 2 (L2)	707.6 - Lowest	10.1	28
Feeder 3 (L3)	906.2 - Lowest	5.38	17
Feeder 4 (L4)	761.6 - Lowest	4.61	12
Feeder 5 (L5)	832.9 -Lowest	8.60	21
Busbar	2303.1 - Highest		

power distribution network extend from the substation in a complex tree-like manner, Figure 4 was therefore simplified to show the interconnection between the network and the controller. The rating of each DG is 7MW. The maximum reactive power output of each DG will be in accordance with the South African Grid Code for renewable power plants which requires that category B DGs import/export a maximum reactive power magnitude that is at least 22.8% of their rated active power [43]. To be able to interface the power distribution network with the control system, voltage magnitudes of several locations were measured. Since the system is based on fault levels, the highest and lowest fault levels on each of the five feeders were found and represented on Table 1. In addition to highest and lowest fault level locations, the voltage magnitudes at the DGs points of connection were also measured. All these measurements were used by the controller to compute different parameters for optimal voltage regulation and power factor improvement. Table 1 also shows the length and loading of each feeder. The network of Figure 5 is similar to that of Figure 4, however, the total number of DGs has been increased to six.

The power distribution networks of Figures 4 and 5 were modelled in MATLAB SIMULINK to test the efficiency of the control system.

Table 1 shows the lowest fault levels in each feeder where the voltage magnitudes were measured. The locations of lowest fault level were chosen as they represent the weakest points on the power distribution network where voltage magnitudes are easily influenced. The highest fault level location was common to all feeders, it was the 22kV busbar. Therefore, all feeders will share the highest fault level measurement at the 22kV busbar. There are several methods of calculating fault levels as indicated on [45]. In this paper, MATLAB SIMULINK was used to identify locations of highest and lowest fault levels.

Three scenarios were then developed to test the control system. The major difference between the three scenarios is the active power generated by DGs. Therefore, each scenario will have a different amount of active power generated by DGs to assess how the control system react under different penetration level of DGs. This was done because as the magnitude of active power generated by DGs changes, the power flow through the power distribution network and the voltage magnitudes also changes. In scenario 1, DGs injected a total active power of 10.92MW. This amount of active power did not overwhelm the power distribution network as voltage magnitudes did not increase significantly. In scenario 2, DGs injected a total active power of 19.58MW, this caused reverse power flow and high voltage magnitudes. The control system operated to alleviate increased voltage magnitudes. In scenario 3, DGs injected a total active power of 34.82MW, this caused extreme reverse power flow and high voltage magnitudes. In this scenario, the control system also operated and alleviate the voltage problem.

A. SCENARIO 1: A POWER DISTRIBUTION NETWORK WITH FIVE 22kV LINES AND FOUR DGs WITH LOW ACTIVE POWER GENERATION

The first test involved the network of Figure 4 where an OLTC equipped power transformer is supplying five 22kV feeders and DGs are exporting low magnitude of active power to the power distribution network. Since the highest fault level location is common to all feeders and located at the 22kV busbar, "feeder 1-5 Voltage" on all Tables will refer to the voltage magnitude at the location of lowest fault level on that feeder. In addition, since DG 1 is connected at the location of lowest fault level on feeder 2, the voltage magnitude at the point of connection for DG 1 and the voltage magnitude at the lowest fault level location of feeder 2 will be similar. Therefore, only one of the two voltage magnitudes will appear on the results Tables.

During low active power generation by DGs, all voltage magnitudes are within the required 5% deviation from nominal voltage, and the substation busbar voltage is the highest voltage magnitude at 1.027p.u. However, when the active power generation of DGs increases, voltage magnitudes will rise above the 5% voltage deviation, and the substation busbar will no longer be the highest voltage magnitude as portrayed in Scenario 2. It is under such circumstance of high voltage magnitudes due to increased DG generation that the

TABLE 2. Power distribution network conditions for scenario 1.

DG1 Active Power	1.67MW	**Feeder 4 Voltage**	1.00p.u
DG2 Active Power	2.51MW	**Feeder 5 Voltage**	1.009p.u
DG3 Active Power	2.31MW	**DG1 Reactive Power**	0MVAR
DG4 Active Power	4.43MW	**DG2 Reactive Power**	0MVAR
DG1 POC Voltage	1.009p.u	**DG3 Reactive Power**	0MVAR
DG2 POC Voltage	1.022p.u	**DG4 Reactive Power**	0MVAR
DG3 POC Voltage	1.005p.u	**OLTC Voltage**	1.027p.u
DG4 POC Voltage	1.020p.u	**OLTC Tap Position**	5
Feeder 1 Voltage	0.999p.u	**Transformer Reactive Power**	1.184MVAR
Feeder 3 Voltage	0.987p.u	**Power Factor**	0.99 Lagging

TABLE 3. Initial conditions for scenario 2, before any voltage regulation.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.063p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	0MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	0MVAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	0MAVR
DG1 POC Voltage	1.139p.u	**DG4 Reactive Power**	0MVAR
DG2 POC Voltage	1.145p.u	**Calculated OLTC Voltage**	0.926p.u
DG3 POC Voltage	1.061p.u	**Actual OLTC Voltage**	1.064p.u
DG4 POC Voltage	1.074p.u	**OLTC Tap Position**	5
Feeder 1 Voltage	1.035p.u	**Transformer Reactive Power**	1.62MVAR
Feeder 3 Voltage	1.043p.u	**Power Factor**	0.98 Lagging
Feeder 4 Voltage	1.036p.u		

conventional OLTC voltage regulation is not effective and the proposed control system is essential. Therefore, scenario 2 will explore a power distribution where the active power generated by the DGs has been increased.

B. SCENARIO 2: A POWER DISTRIBUTION NETWORK WITH FIVE 22kV LINES AND FOUR DGs WITH MEDIUM ACTIVE POWER GENERATION

The second test involved the network of Figure 4 where the OLTC equipped power transformer is supplying five 22kV lines and four DGs are connected to the network. The initial conditions of the system are shown in Table 3. It should be noted that the increased voltage magnitudes are due to increased DGs active power generation since the OLTC tap position has not changed from scenario 1.

Initially the substation busbar voltage was at 1.064p.u and DGs 1-4 POC voltage magnitudes at 1.139, 1.145, 1.061 and 1.074p.u. These are high voltage magnitudes as multiple power utility companies prefer a maximum voltage aberration of 5% from nominal voltage. At this point, the control system calculated that the OLTC reference voltage should be 0.926p.u based on the computed average network voltage of 1.075p.u and a voltage deviation of 0.075p.u from nominal voltage. The calculated OLTC reference voltage of 0.926p.u was lower than the measured OLTC substation voltage of 1.064p.u. However, the control system delayed the OLTC action and allowed DGs to regulate voltage first. The results continue in Table 4.

TABLE 4. When DGs are importing reactive power locally at their point of connection for voltage regulation.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.001p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	-1.23MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	-1.50MVAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	0.26MVAR
DG1 POC Voltage	1.045p.u	**DG4 Reactive Power**	-0.29MVAR
DG2 POC Voltage	1.048p.u	**Calculated OLTC Voltage**	0.998p.u
DG3 POC Voltage	0.989p.u	**Actual OLTC Voltage**	0.997p.u
DG4 POC Voltage	1.011p.u	**OLTC Tap Position**	5
Feeder 1 Voltage	0.970p.u	**Transformer Reactive Power**	4.56MVAR
Feeder 3 Voltage	0.973p.u	**Power Factor**	0.87 Lagging
Feeder 4 Voltage	0.972p.u		

DGs 1, 2 and 4 imported 1.23, 1.50 and 0.29MVAR, respectively. This reactive power import increased the reactive power flow through the transformer from 1.62MVAR to 4.56MVAR. As a result, the voltage magnitudes at the substation busbar and DGs 1-4 POC dropped to 0.997, 1.045, 1.048, 0.989, and 1.011p.u, respectively. At this moment, the control system recalculated the OLTC reference voltage to 0.998p.u which is the same as the measured OLTC substation voltage of 0.997p.u considering a 0.01p.u error margin. The calculated OLTC reference voltage had increased from 0.926p.u to 0.998p.u since the overall average network voltage decreased from 1.075p.u to 1.001p.u when DGs imported reactive power.

Since the calculated OLTC reference voltage is equal to the OLTC substation voltage, the voltage regulation effort of DGs is therefore enough, and the OLTC did not have to change its current tap position. However, since importing reactive power increased reactive power flow and hence dropped the power factor from 0.98 to 0.87, the system tried to correct it. DGs 1, 2, 3 and 4 were utilising 77%, 93%, 16% and 18% of their reactive power capacity for voltage control, respectively. Therefore, the control system chose DGs 3 and 4 to correct the power factor and allocated a maximum reactive power

TABLE 5. When all DGs are importing/exporting reactive power for voltage control and power factor improvement.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.026p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	-1.64MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	-1.65MVAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	1.27MVAR
DG1 POC Voltage	1.062p.u	**DG4 Reactive Power**	1.19MVAR
DG2 POC Voltage	1.066p.u	**Calculated OLTC Voltage**	0.975p.u
DG3 POC Voltage	1.018p.u	**Actual OLTC Voltage**	1.021p.u
DG4 POC Voltage	1.036p.u	**OLTC Tap Position**	5
Feeder 1 Voltage	0.994p.u	**Transformer Reactive Power**	3.55MVAR
Feeder 3 Voltage	1.00p.u	**Power Factor**	0.92 Lagging
Feeder 4 Voltage	0.994p.u		

of 2.28MVAR to each of the two DGs. The system further computed the reactive power available to DGs 3 and 4 for power factor correction based on reactive power capacity and POC voltage magnitude to 1.01MVAR and 1.48MVAR, respectively. Since the available reactive power was lower than the maximum allocated reactive power, the available reactive power was therefore used for power factor correction. The results continue in Table 5.

Based on the reactive power computed by the control system for both voltage regulation and power factor correction, DGs 3 and 4 exported 1.27MVAR and 1.19MVAR, respectively. This enhanced power factor from 0.87 to 0.92. However, exporting reactive power to correct power factor slightly increased voltage magnitudes.

Since the voltage magnitudes that increased above 5% of nominal voltage was that of DGs 1 and 2 POC, and they had imported their rated reactive power capacity, they could not do anything further. The control system then called upon the OLTC to take over. The reference voltage of the OLTC was calculated to be 0.975p.u based on the overall average network voltage of 1.025p.u and an average voltage aberration of 0.025p.u from nominal voltage. Since the calculated OLTC reference voltage of 0.975p.u is lower than the measured OLTC substation busbar voltage of 1.021p.u, the OLTC then changed tap position once in attempt to equalize the two voltage magnitudes. Results continue in Table 6.

After the OLTC has changed tap position once, the measured voltage at the substation busbar reduced from 1.021p.u to 1.014p.u. As the overall average network voltage magnitude decreases from 1.025p.u to 1.018p.u, the control system also adjusted the reactive power of DGs doing power factor correction improving it further from 0.92 to 0.94. The control system then recalculated the OLTC reference voltage to 0.981p.u which was still below the measured voltage

TABLE 6. When all DGs are importing/exporting reactive power and the OLTC has tapped once.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.021p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	-1.63MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	-1.64MVAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	1.58MVAR
DG1 POC Voltage	1.057p.u	**DG4 Reactive Power**	1.35MVAR
DG2 POC Voltage	1.061p.u	**Calculated OLTC Voltage**	0.981p.u
DG3 POC Voltage	1.01p.u	**Actual OLTC Voltage**	1.014p.u
DG4 POC Voltage	1.032p.u	**OLTC Tap Position**	6
Feeder 1 Voltage	0.987p.u	**Transformer Reactive Power**	2.94MVAR
Feeder 3 Voltage	0.992p.u	**Power Factor**	0.94 Lagging
Feeder 4 Voltage	0.987p.u		

TABLE 7. When all DGs are importing/exporting reactive power and OLTC has tapped twice.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.015p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	-1.57MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	-1.63MVAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	1.59MVAR
DG1 POC Voltage	1.049p.u	**DG4 Reactive Power**	1.54MVAR
DG2 POC Voltage	1.053p.u	**Calculated OLTC Voltage**	0.991p.u
DG3 POC Voltage	0.997p.u	**Actual OLTC Voltage**	1.004p.u
DG4 POC Voltage	1.025p.u	**OLTC Tap Position**	7
Feeder 1 Voltage	0.977p.u	**Transformer Reactive Power**	2.49MVAR
Feeder 3 Voltage	0.980p.u	**Power Factor**	0.95 Lagging
Feeder 4 Voltage	0.978p.u		

of 1.014p.u and hence another tap position change was initiated. Results continue in Table 7.

After the OLTC has changed tap position a second time, the measured voltage at the OLTC substation busbar dropped further from 1.014p.u to 1.004p.u. As the overall average network voltage dropped further from 1.018p.u to 1.011p.u due to OLTC action, the control system adjusted the reactive power output of DGs for optimal power factor management improving the power factor further from 0.94 to 0.95. The OLTC reference voltage was also recalculated to 0.991p.u which was still lower than the measured busbar voltage of 1.004p.u. Therefore, another tap position change was initiated. Results continue in Table 8.

TABLE 8. All DGs importing/exporting reactive power and OLTC has tapped three times.

DG1 Active Power	5.67MW	**Feeder 5 Voltage**	1.008p.u
DG2 Active Power	4.50MW	**DG1 Reactive Power**	-1.33MVAR
DG3 Active Power	3.10MW	**DG2 Reactive Power**	-1.56VAR
DG4 Active Power	6.31MW	**DG3 Reactive Power**	1.45MVAR
DG1 POC Voltage	1.046p.u	**DG4 Reactive Power**	1.24MVAR
DG2 POC Voltage	1.049p.u	**Calculated OLTC Voltage**	0.998p.u
DG3 POC Voltage	0.986p.u	**Actual OLTC Voltage**	0.994p.u
DG4 POC Voltage	1.019p.u	**OLTC Tap Position**	8
Feeder 1 Voltage	0.970p.u	**Transformer Reactive Power**	2.03MVAR
Feeder 3 Voltage	0.968p.u	**Power Factor**	0.97 Lagging
Feeder 4 Voltage	0.969p.u		

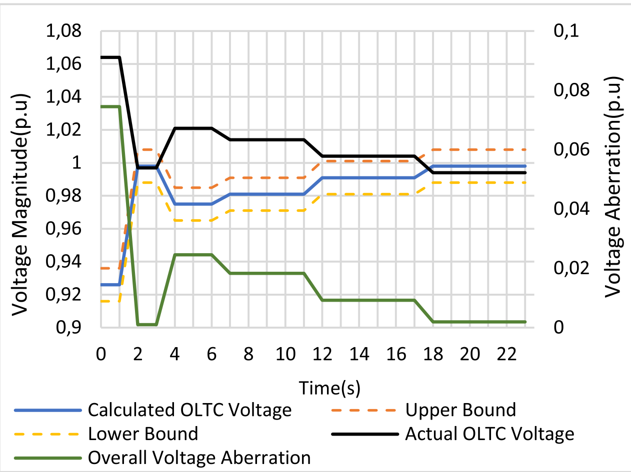

FIGURE 6. Substation busbar voltage, calculated OLTC reference voltage, and average network voltage aberration from nominal voltage.

After the OLTC has changed tap position a third time, the substation busbar voltage dropped to 0.994p.u whereas the recalculated reference voltage was calculated to 0.998p.u based on a 1.001p.u overall average network voltage and 0.001p.u average voltage deviation from nominal voltage. Since the measured substation busbar voltage and the calculated OLTC reference voltage were within an error margin of 0.01p.u from each other, the control system instructed the OLTC to stop changing tap positions. The control system also readjusted the output reactive power of all DGs further improving the power factor from 0.95 to 0.97. Figures 6-9 visually shows the continuous operation for scenario 2. The results presented in Figures 6-9 shows the 1 second average analogue values obtained when the proposed control system was tested as per scenario 2.

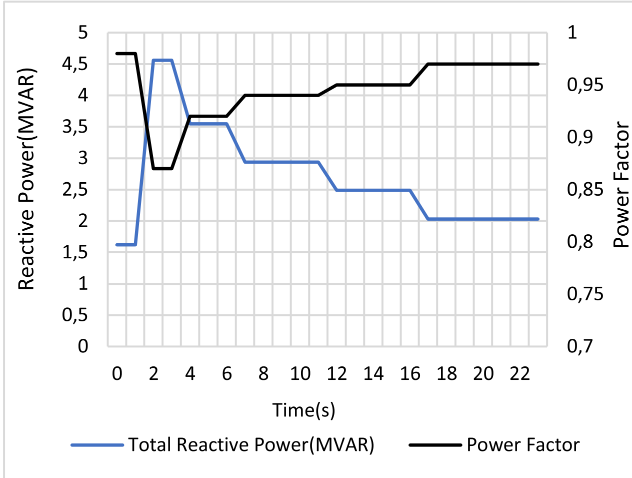

FIGURE 7. Total reactive power and the power factor.

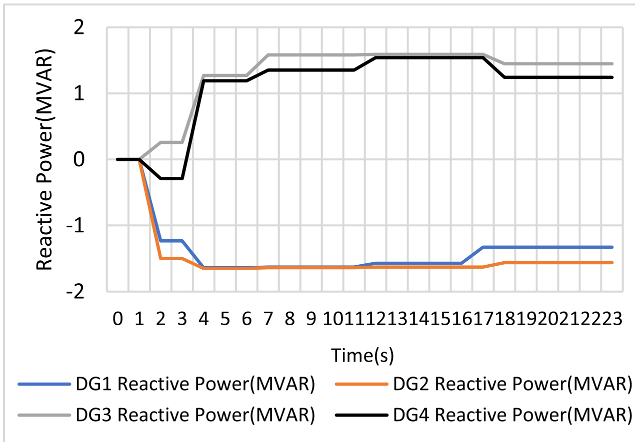

FIGURE 8. Reactive Power output of individual DGs.

Figure 6 shows the OLTC calculated reference voltage, the substation measured busbar voltage magnitude and the average network voltage deviation from nominal voltage. Initially, the calculated OLTC reference voltage and the measured busbar voltage are further apart. This is due to the average voltage deviation which is 0.075p.u from nominal voltage. As DGs import reactive power for voltage regulation, the calculated reference voltage, and the measured busbar voltage match without any OLTC action at t = 2 s. At this point, the network average voltage magnitude also matches the nominal voltage resulting in a 0.001p.u voltage deviation from nominal voltage. However, at t = 4 s, power factor correction causes a mismatch again on the calculated OLTC reference voltage and the measured substation voltage since exporting reactive power increased average voltage deviation from 0.001p.u to 0.025p.u. Hence, the OLTC changed tap positions three times until the calculated OLTC reference voltage and the measured voltage are matched again with a 0.01p.u error margin. Since the objective of the control system is to reduce network average voltage deviation from nominal voltage, it managed to reduce network average voltage deviation from 0.075p.u to 0.001p.u.

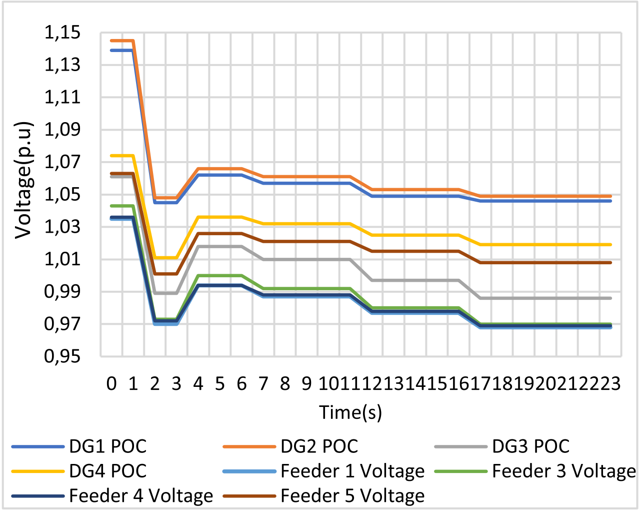

FIGURE 9. DGs POC and measured locations voltage magnitudes.

Figure 7 shows the sum of reactive power flowing through the substation transformer together with the accompanying power factor. When DGs import reactive power for voltage control at t = 1 s, reactive power flowing through the transformer increased from 1.62 to 4.56MVAR, and power factor decreased from 0.98 to 0.87. The power factor correction attribute of the control system then improved the power factor from 0.87 to 0.97 as time progressed.

Figure 8 shows the output reactive power of each DG as the control system controlled each DG individually. All DGs started at 0MVAR, then DGs 1 and 2 absorbed reactive power to control voltage at t = 1 s whereas DGs 3 and 4 went to power factor correction mode at t = 3 s. The control system then started regulating the reactive power output of all DGs individually to optimise both voltage regulation and power factor correction as time progressed.

Figure 9 shows the voltage magnitudes throughout the power distribution network where measurements were taken. It can be observed that voltage magnitudes at the DG POC are high at the beginning but decreases significantly as the control system controls voltage through DGs and the OLTC.

Scenario 2 has portrayed that high voltage magnitudes are experienced during increased DG active power generation. However, the control system managed to reduce those high voltage magnitudes down to acceptable range. It was also observed that the control system would instruct a DG to import a large amount of reactive power when the voltage magnitude at its POC is further above 1.p.u and also instruct it to export large amount of reactive power when the voltage magnitude is further below 1.p.u. A smaller voltage deviation from 1.p.u also prompted a small import/export of reactive power depending on the direction of the voltage deviation. In addition, the OLTC also equalized the calculated reference voltage and the busbar voltage. This combined effort of DGs and the OLTC improved voltage magnitudes and enhanced power factor. Based on these results, it can be deduced that the proposed control system enables high penetration of DGs in a power distribution network while keeping voltage magnitudes and power factor well regulated.

TABLE 9. Initial conditions before voltage regulation or power factor correction.

DG1 Active Power	5.97MW	**Feeder 4 Voltage**	1.035p.u
DG2 Active Power	6.39MW	**Feeder 5 Voltage**	1.057p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	0MVAR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	0MVAR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	0MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	0MVAR
DG1 POC Voltage	1.146p.u	**DG5 Reactive Power**	0MVAR
DG2 POC Voltage	1.135p.u	**DG6 Reactive Power**	0MVAR
DG3 POC Voltage	1.051p.u	**Calculated OLTC Voltage**	0.919p.u
DG4 POC Voltage	1.061p.u	**Actual OLTC Voltage**	1.054p.u
DG5 POC Voltage	1.087p.u	**OLTC Tap Position**	7
DG6 POC Voltage	1.117p.u	**Transformer Reactive Power**	2.65MVAR
Feeder 3 Voltage	1.033p.u	**Power Factor**	0.98 Lagging

C. SCENARIO 3: A NETWORK WITH FIVE 22kV FEEDERS AND SIX DGs WITH HIGH ACTIVE POWER GENERATION

The third test will involve the network of Figure 5 with an OLTC equipped power transformer supplying five 22kV feeders and six DGs connected to the network. The purpose is to evaluate how the proposed algorithm performs when the number of DGs and the active power they generate has increased further compared to scenario 2. The results are shown in Tables 9-14.

Initially, the voltage magnitude at the OLTC regulated substation busbar is 1.054p.u and the POC voltage magnitudes for DGs 1-6 are at 1.146, 1.135, 1.051, 1.061, 1.087 and 1.117p.u, respectively. Upon noticing that these are high voltage magnitudes that exceed 5% of the nominal voltage, the control system initiated the voltage regulation process. It calculated the reference voltage of the OLTC to 0.919p.u based on the network overall average voltage of 1.080p.u and 0.080p.u average voltage aberration from nominal voltage. Since the calculated OLTC reference voltage of 0.919p.u is lower than the measured substation busbar voltage of 1.054p.u, an OLTC tap change signal was generated. However, the control system placed the OLTC on time delay and allowed DGs to regulate voltage first. Therefore, the reactive power of all DGs desired for voltage control was then calculated. Results continues in Table 10.

DGs 1-6 imported 1.65, 1.63, 0.31, 0.63, 1.01 and 1.64MVAR, respectively. This reduced the measured substation busbar voltage from 1.054 to 1.020p.u. Similarly,

TABLE 10. DGs importing reactive power for voltage control based on local measurements.

DG1 Active Power	5.97MW	**Feeder 4 Voltage**	1.002p.u
DG2 Active Power	6.39MW	**Feeder 5 Voltage**	1.022p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	-1.65MVAR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	-1.63MVAR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	-0.31MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	-0.63MVAR
DG1 POC Voltage	1.064p.u	**DG5 Reactive Power**	-1.01MVAR
DG2 POC Voltage	1.055p.u	**DG6 Reactive Power**	-1.64MVAR
DG3 POC Voltage	1.012p.u	**Calculated OLTC Voltage**	0.969p.u
DG4 POC Voltage	1.027p.u	**Actual OLTC Voltage**	1.020p.u
DG5 POC Voltage	1.039p.u	**OLTC Tap Position**	7
DG6 POC Voltage	1.062p.u	**Transformer Reactive Power**	9.96MVAR
Feeder 3 Voltage	0.995p.u	**Power Factor**	0.79 Lagging

the POC voltage for DGs 1-6 reduced to 1.064, 1.055, 1.012, 1.027, 1.039 and 1.062p.u, respectively. The control system recalculated the OLTC reference voltage to 0.969p.u based on the reduced average network voltage of 1.030p.u and 0.030p.u average voltage aberration from nominal voltage. Since the calculated OLTC reference voltage of 0.969p.u was lower than the measured substation voltage of 1.020p.u, the initial tap change signal generated was sustained. However, since the OLTC was still on time delay, the control system prompted DGs to correct the power factor first.

This is because the power factor had reduced from 0.98 to 0.79 when DGs imported reactive power and increased reactive power flow from 2.65 to 9.96MVAR. Since DGs 1-6 were dispatching 103%, 101%, 19%, 40%, 63%, and 102% of reactive power in relation to their rated reactive power capability for voltage regulation, respectively. The control system then selected DGs 3 and 4 to assist in correcting the power factor and allocated a maximum reactive power of 4.41MVAR to each of the two DGs. It further calculated the reactive power available to each of the two DGs for power factor correction based on capacity and POC voltage magnitudes to 1.17 and 0.85MVAR, respectively. Since available reactive power was lower than the maximum reactive power, the available reactive power was used for power factor enhancement. Results continue in Table 11.

DGs 3 and 4 then changed from importing to exporting 0.86 and 0.22MVAR, respectively, this enhanced the power factor from 0.79 to 0.84. Exporting reactive power for power factor correction boosted voltage magnitudes slightly. Hence, based on the average network voltage that has increased from 1.030p.u to 1.040p.u when DGs exported reactive power to enhance power factor, the control system recalculated the OLTC reference voltage to 0.960p.u. Since this was still below the measured substation voltage of 1.028p.u, the initial tap position change signal generated earlier was still sustained. When the time delay elapses, the OLTC changed tap position once. Results continue in Table 12.

TABLE 11. DGs doing voltage regulation and reactive power compensation for power factor correction.

DG1 Active Power	5.97MW	**Feeder 4 Voltage**	1.010p.u
DG2 Active Power	6.39MW	**Feeder 5 Voltage**	1.035p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	-1.65MVAR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	-1.64MVAR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	0.86MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	0.22MVAR
DG1 POC Voltage	1.069p.u	**DG5 Reactive Power**	-1.32MVAR
DG2 POC Voltage	1.061p.u	**DG6 Reactive Power**	-1.65MVAR
DG3 POC Voltage	1.024p.u	**Calculated OLTC Voltage**	0.960p.u
DG4 POC Voltage	1.040p.u	**Actual OLTC Voltage**	1.028p.u
DG5 POC Voltage	1.046p.u	**OLTC Tap Position**	7
DG6 POC Voltage	1.068p.u	**Transformer Reactive Power**	8.28MVAR
Feeder 3 Voltage	1.007p.u	**Power Factor**	0.84 Lagging

TABLE 12. All DGs importing/exporting reactive power and OLTC has tapped once.

DG1 Active Power	5.97MW	**Feeder 4 Voltage**	0.996p.u
DG2 Active Power	6.39MW	**Feeder 5 Voltage**	1.027p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	-1.65MAVR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	-1.62MAVR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	1.44MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	0.62MVAR
DG1 POC Voltage	1.060p.u	**DG5 Reactive Power**	-0.86MVAR
DG2 POC Voltage	1.052p.u	**DG6 Reactive Power**	-1.64MVAR
DG3 POC Voltage	1.012p.u	**Calculated OLTC Voltage**	0.970p.u
DG4 POC Voltage	1.031p.u	**Actual OLTC Voltage**	1.015p.u
DG5 POC Voltage	1.035p.u	**OLTC Tap Position**	8
DG6 POC Voltage	1.058p.u	**Transformer Reactive Power**	6.78MVAR
Feeder 3 Voltage	0.994p.u	**Power Factor**	0.88 Lagging

After the OLTC has changed tap position once, the substation busbar voltage dropped to 1.015p.u. The control system

TABLE 13. All DGs importing/exporting reactive power and OLTC has tapped twice.

DG1 Active Power	5.97MW	**Feeder 4 Voltage**	0.983p.u
DG2 Active Power	6.39MW	**Feeder 5 Voltage**	1.018p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	-1.63MVAR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	-1.43MVAR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	1.67MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	1.04MVAR
DG1 POC Voltage	1.055p.u	**DG5 Reactive Power**	-0.58MVAR
DG2 POC Voltage	1.047p.u	**DG6 Reactive Power**	-1.49MVAR
DG3 POC Voltage	0.998p.u	**Calculated OLTC Voltage**	0.979p.u
DG4 POC Voltage	1.023p.u	**Actual OLTC Voltage**	1.002p.u
DG5 POC Voltage	1.025p.u	**OLTC Tap Position**	9
DG6 POC Voltage	1.048p.u	**Transformer Reactive Power**	5.39MVAR
Feeder 3 Voltage	0.981p.u	**Power Factor**	0.92 Lagging

TABLE 14. All DGs importing/exporting reactive power and OLTC has tapped three times.

DG1 Active Power	5.97MW	**Feeder 4 End Voltage**	0.974p.u
DG2 Active Power	6.39MW	**Feeder 5 End Voltage**	1.012p.u
DG3 Active Power	5.90MW	**DG1 Reactive Power**	-1.63MVAR
DG4 Active Power	5.87MW	**DG2 Reactive Power**	-1.26MVAR
DG5 Active Power	5.31MW	**DG3 Reactive Power**	1.63MVAR
DG6 Active Power	5.38MW	**DG4 Reactive Power**	1.31MVAR
DG1 POC Voltage	1.051p.u	**DG5 Reactive Power**	1.02MVAR
DG2 POC Voltage	1.045p.u	**DG6 Reactive Power**	-1.44MVAR
DG3 POC Voltage	0.988p.u	**Calculated OLTC Voltage**	0.985p.u
DG4 POC Voltage	1.017p.u	**Actual OLTC Voltage**	0.992p.u
DG5 POC Voltage	1.024p.u	**OLTC Tap Position**	10
DG6 POC Voltage	1.048p.u	**Transformer Reactive Power**	3.32MVAR
Feeder 3 End Voltage	0.971p.u	**Power Factor**	0.96 Lagging

then recalculated the OLTC reference voltage to 0.970p.u based on the new average network voltage of 1.029p.u and a 0.029p.u voltage aberration from nominal voltage. As the average network voltage magnitude drops, the control system also adjusted the DGs reactive power output improving the power factor from 0.84 to 0.88. Since the calculated OLTC reference voltage of 0.970p.u was still below the measured busbar voltage of 1.015p.u, another OLTC tap position change was initiated. Results continue in Table 13.

After the OLTC has changed tap position a second time, the substation busbar voltage dropped to 1.002p.u. The control system then recalculated the new OLTC reference voltage to 0.979p.u based on the new overall average network voltage magnitude of 1.019p.u and a 0.019p.u average voltage aberration from nominal voltage. The control system also adjusted the reactive power output of DGs to enhance the power factor. In addition, since DG 5 reactive power output for voltage regulation has dropped below 50% of rated reactive power to 36%, the control system then changed its status to include both voltage regulation and power factor management. DG 5 then changed from importing 0.58MVAR to exporting 1.02MVAR. Since the calculated OLTC reference voltage was still below the measured busbar voltage, another tap position change was initiated. Results continue in Table 14.

After the third tap position change, the substation busbar voltage dropped to 0.992p.u. The control system recalculated the OLTC reference voltage to 0.985p.u based on an overall average network voltage of 1.014p.u and a 0.014p.u voltage aberration from nominal voltage. Since the calculated OLTC reference voltage and the measured substation busbar voltage were within 0.01p.u error margin of each other, the tap position change stopped. The system also adjusted the DGs reactive power output and hence improved the power factor further from 0.92 to 0.96. Figures 10-13 visually shows the continuous operation for scenario 3.

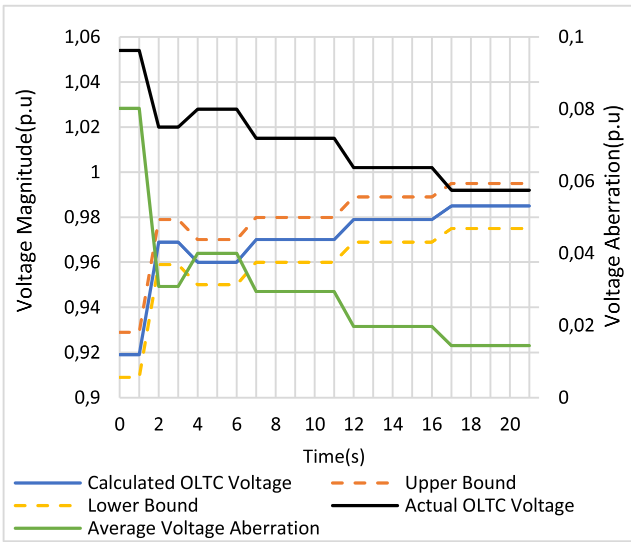

FIGURE 10. Substation busbar voltage, calculated OLTC reference voltage and network voltage aberration from nominal voltage.

In Figure 10, initially, the actual substation busbar voltage and the calculated OLTC reference voltage are further apart. This is due to the difference in average voltage magnitude and the nominal voltage leading to an average voltage deviation of 0.08p.u from nominal voltage. The import of reactive power by DGs for voltage control at t = 2 s slightly brings the

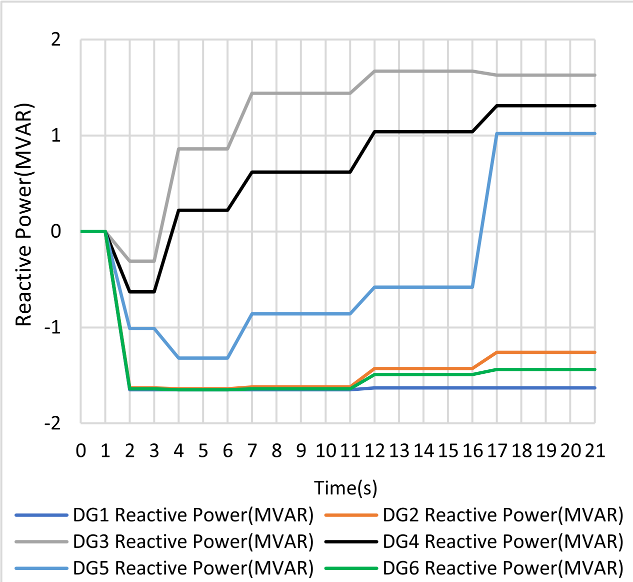

FIGURE 11. Reactive power output for each DG for Scenario 3.

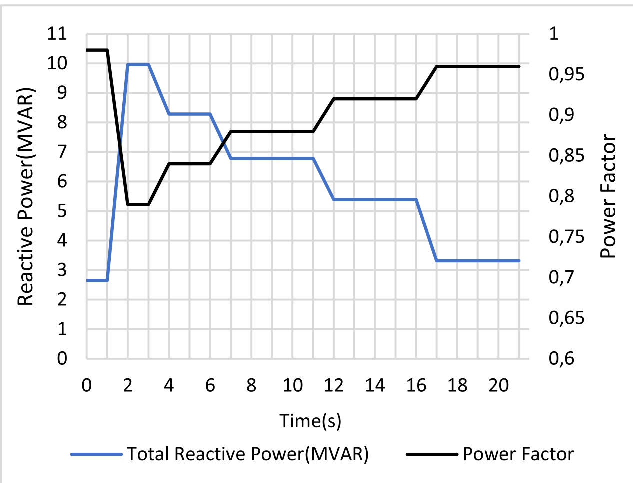

FIGURE 12. Total reactive power and the power factor for scenario 3.

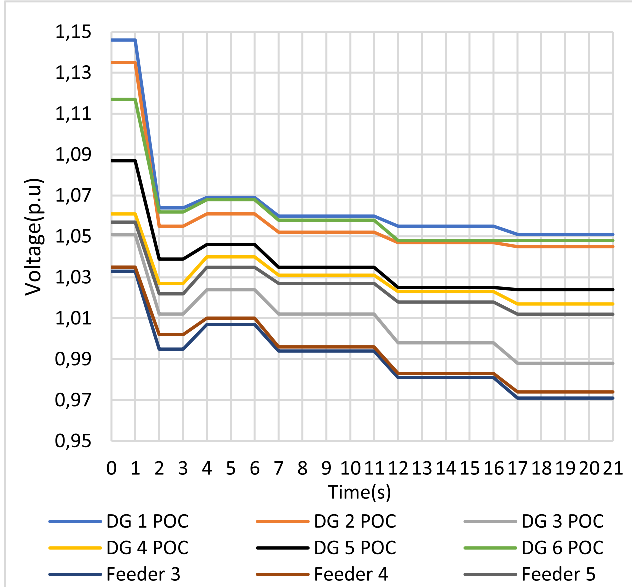

FIGURE 13. Voltage magnitudes of measured locations for scenario 3.

calculated OLTC reference voltage and the measured busbar voltage closer to each other but still not close enough to prevent the OLTC from changing tap position.

However, the action by DGs to correct the power factor at $t = 3$ s drift the calculated OLTC reference voltage and the measured substation busbar voltage further apart again. The export of reactive power to enhance power factor also increased the average voltage deviation from 0.031p.u to 0.04p.u. When DGs have implemented voltage regulation and did not successfully equalize the calculated OLTC reference voltage and the OLTC substation measured voltage, the control system called upon the OLTC to equalize the two voltage magnitudes. As a result, the OLTC changed tap positions three times until the calculated and measured voltage magnitudes were matched with a 0.01p.u error margin. Since the objective of the control system is to reduce overall average network voltage deviation from nominal voltage, it successfully reduced average voltage deviation from 0.080p.u to 0.014p.u.

As shown in Figure 11, while the control system was controlling the OLTC to equalize the calculated OLTC reference voltage and the measured substation voltage, it was simultaneously adjusting the output reactive power of each individual DG to ensure optimal voltage regulation and power factor correction.

Figure 12 indicate how the total reactive power flowing through the substation transformer together with the power factor were changing as the control system was adjusting individual DG reactive power output. It can be observed that as the control system was making voltage regulation efforts, it was simultaneously making adjustments that improves the power factor. The power factor improved from 0.79 at $t = 2$ s to 0.96 at $t = 17$ s.

Figure 13 shows the voltage magnitudes in locations that were measured on the power distribution network. It can be observed that at the beginning, DG POC voltage magnitudes were very high. However, as the control system coordinate DGs and OLTC for voltage regulation, the voltage magnitudes dropped to acceptable range. The results presented in Figures 10-13 shows the 1 second average analogue values obtained when the proposed control system was tested as per scenario 3.

Scenarios 2 and 3 have demonstrated the capability of the proposed control system in regulating voltage magnitudes and managing the power factor. Based on scenarios 2 and 3, it can be deduced that the proposed control system is an intelligent scheme that simultaneously control multiple variables including the OLTC tap position, DGs reactive power output for voltage regulation, and DGs reactive power output for power factor correction. The proposed control system constantly adjusts these three variables in real time to achieve the objectives of minimising the network average voltage deviation from nominal voltage and maximising the power system power factor. Since the proposed control system can effectively control voltage magnitudes during high active power generation by DGs, it can therefore allow more DGs to be connected to the power distribution network.

V. CONCLUSION

An advanced voltage regulation scheme is introduced on this paper that allows the medium voltage power distribution network to optimally regulate voltage and improve the power factor when multiple DGs are connected. While the conventional OLTC voltage regulation philosophy changes substation voltage based on a fixed reference voltage, the proposed control scheme calculates an OLTC reference voltage based on overall average network voltage magnitude. In operation, the control system uses DGs for voltage regulation first since they are quicker than the mechanical OLTC. The OLTC is called upon if DGs cannot successfully regulate voltage. Simultaneously, the control system adjusts the reactive power output of DGs as the voltage changes such that it improves the power factor of the power system as well. The proposed control system was tested in a South African 22kV medium voltage power distribution network that was modelled in MATLAB SIMULINK. The assessment was carried through a series of three scenarios which tested different penetration level of DGs. In scenario 2, the control system managed to drive the substation busbar voltage from 1.063p.u to 0.994p.u in accordance with the calculated OLTC reference voltage. During the same period, the overall average network voltage reduced from 1.075p.u to 1.001p.u. In addition, the power factor also improved from 0.87 to 0.97 during the same time. Similarly, in scenario 3, the control system changed the substation voltage from 1.053p.u to 0.992p.u, and the overall average network voltage reduced from 1.080p.u to 1.014p.u. The power factor also improved from 0.79 to 0.96 during the same period. Based on the attained results, it can be concluded that the proposed control system can effectively control voltage magnitudes of a medium voltage power distribution network while using the overall network average voltage and also enhance the power factor when DGs are connected.

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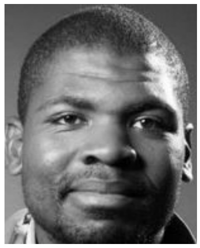

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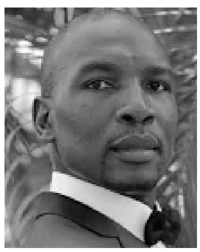

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