Reduction of Switching Operations of Reactive Power Controlling Devices

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***Abstract*—The involvement of Non-Dispatchable Distributed Generation (NDDG) in Distribution System (DS) increases the Switching Operations (SOs) of Underload Tap Changer (ULTC) and Shunt Capacitors (SCs). This decreases the life of ULTC and SCs, therefore in this paper a novel method is proposed for decreasing the SOs of ULTC and SCs. The proposed method involves two stages in first stage forecasting of load and forecasting of output power of two 3MWs DFIGs. The load and DFIG output power is forecasted using ANFIS model. The second stage involves reactive power scheduling between DFIGs, ULTC and SCs by minimizing SOs, power loss and Steady State Voltage Fluctuations (SSVF) using Particle Swarm Optimization (PSO) method. the proposed method is implemented on 10kV south Korean Distributed system. the performance of proposed method is compared with conventional method, from the findings it is clear that the proposed method is effectively reducing the objectives when compared with conventional and irrespective of location of DFIGs.**

Keywords*— *Non-Dispatchable Distributed Generation (NDDG), Switching Operations (SOs), Steady State Voltage Fluctuations (SSVF).

I. INTRODUCTION

In recent years, distributed generation (DG), which includes photovoltaic (PV), wind power generation, fuel cells, and microturbines, has received a lot of attention. The increased use of DG will have a significant impact on the control and operation of distribution networks (DNs). There will be a significant impact on voltage distribution and power flow direction. When DG increases in the DN using standard control methods, voltage variation or steady-state voltage fluctuation becomes a problem. The typical reactive power control technique faces new challenges and requirements [1]. Because of its high penetration, DG's reactive power could be used to provide ancillary services in an economical and effective manner [2]. Traditional distribution systems use unidirectional power transmission from high voltage networks to intermediate or low voltage feeders. Bidirectional power flow may result from the incorporation of DG, potentially causing overvoltage and interfering with standard voltage regulation [3]. Several research have been carried out on classical steady-state voltage control in distribution systems [4]. On-load tap changing (OLTC), line regulators, shunt capacitors (Sh.Cs), reactors, and other components are principally responsible for DN voltage regulation.

Research into reactive power coordination control using DG is gaining prominence. The coordination problem is often represented as an optimization problem [5–10]. [5] proposed an approach to integrated local and remote voltage regulation in a distribution system that considered DG, OLTC transformers, and capacitors. Viawan and Karlsson [6] shown how OLTC, feeder capacitors, substation capacitors, and DG should be correctly coordinated. Other research investigated the coordination of DG and traditional reactive power devices as an optimal power flow (OPF) problem [7-8]. Dent et al. estimated a network's ability to manage DG with voltage step limits using a well-established OPF-based method [7]. An OPF technique that seeks to optimize DG power generation while reducing network losses was put out by Ahmadi et al. [8]. A trust region sequential quadratic programming (TRSQP) with branch and bound method for coordinated voltage regulation was proposed in [9] using a one-day-ahead load forecast. Dynamic programming (DP) was introduced in [10] as a method for controlling a DG and voltage control devices simultaneously. In steady-state voltage regulation, the proposed coordinated technique can reduce the ULTC switching operations number (SON) and Sh.Cs. To reduce voltage variance, [11] proposed reactive power regulation of inverters interfaced with DG.

Coordinated voltage control approaches can be classified into three categories. The first class includes online control algorithms that use local quantities to coordinate voltage control devices at a distribution or transmission substation, such as SVC, STATCOM, LTC, or shunt capacitors and reactors [2-6]. To improve the voltage profile and reduce the number of mechanical switching operations, [2] proposed integrating a fast reactive compensation device into a heavily loaded distribution substation and coordinating it with an LTC transformer and mechanically switched capacitors. [3] describes a coordinated control scheme for an SVC and an LTC at the distribution substation that preserves the SVC's operational margin while improving load voltage quality. [4] designed a two-stage slope regulation and two-voltage regulation control technique to limit the SVC's reactive power production during steady state and compensate for the reactive power requirement by coordinating with the LTC. A coordinated voltage control system for the local substation, consisting of STATCOM, shunt capacitor, shunt reactor, and LTC, was implemented in [5] to maintain the rapid reactive power reserve and manage the voltage within a permissible range. In order to limit the number of tap changes of the transformer and STATCOM output and maintain a proper voltage magnitude at the substation bus, an artificial neutral network (ANN) based coordination control approach for LTC transformer and STATCOM has been proposed in [6].

A sensitivity-based strategy to reactive power dispatch has been proposed in [7] in order to keep the voltage profile within a tolerable range and recover the SVC reserve. [8] discusses how an SVC can be used to coordinate the switching of several existing capacitor banks in a large load center (the western section of Entergy's Golf States Inc. (EGSI) service territory). A coordinated voltage control technique for the STATCOM and LTC transformer was published in [9] to improve steady-state and dynamic metrics such as voltage responsiveness, voltage recovery, steady-state STATCOM loads, voltage profile, and maximum critical time of failure. To eliminate voltage violations in system contingencies, a coordinated voltage control for SVCs and STATCOMs was developed and implemented utilizing a learning fuzzy-logic controller and a multi-agent cooperative protocol [10]. Based on the multi-agent system concept and the use of programmable reactive power sources and switched capacitor banks, a method suitable for locations with FACTS devices has been devised in [11] to boost the online reactive reserve for crucial continuity.

The output of linked DG alters the power flow across the distribution system. Reverse power flow can occur as a result of DG output, causing voltage to rise at the point of common coupling (PCC) [12]. A innovative approach to voltage control for managing an on-load tap changer (OLTC) has been proposed [13]. This technique addresses the issue of traditional voltage management in distribution systems using DGs, such as line drop compensators (LDCs). By measuring both the substation transmitting current and the DG current, modified LDC control that takes into account the influence of DGs is implemented. Reference [14] investigates the impact of DGs on OLTC control using LDC by simulating three distinct feeder models, with a focus on the feeder structure, LDC settings, and DG PCC. Multiple line drop compensation (MLDC) is recommended in a distribution system with DGs to evaluate each feeder current and determine the optimal OLTC tap point [15]. For distribution networks with a large number of DGs, fuzzy logic-based OLTC control is recommended [16]. Nonetheless, the coordinated reactive power control of networked DGs is not included in these studies. In [17], a distributed reactive power regulation system is proposed that incorporates shunt capacitors and remote terminal units (RTUs) installed in each DG. The RTUs communicate with one another to adjust the voltage in the distribution system. To control the voltage of distribution systems, RTUs communicate with one another via a communication channel. [18] employs a distributed control technique for voltage regulation in order to improve the voltage profile of a distribution system with many DGs. In [19], the voltage of distribution networks is managed using DG power factor management while accounting for shunt capacitor and OLTC reaction delay. In [20], a two-step voltage control technique is introduced. To regulate the violated bus voltage, the first stage determines the reactive power required by linked DGs. The second phase uses other adjacent bus controllers to compensate for reactive power and manage the voltage in order to reach the desired voltage if the violated bus voltage cannot be locally regulated by the connecting DG owing to capacity constraints. Furthermore, a technique for regulating voltage increases caused by connected DGs is proposed in [21]. To avoid voltage violations, the controller limits the reactive power that the DG injects. [22] describes a distributed voltage control strategy for addressing difficulties caused by a high number of DG linkages. In [23-31], different types of DGs with different algorithms proposed for reactive power loss reduction and reduction of switching operations.

Non-dispatchable distribution generation (NDDG) has received minimal attention in the research literature, with most approaches focusing on single dispatchable distributed generation (DDG). The coordination challenge with numerous DGs is first introduced in this study. The load is then anticipated hourly one day in ahead using the Adaptive Neuro Fuzzy Inference System (ANFIS) method, and the coordination problem is optimized using the Grey Wolf Optimizer (GWO) algorithm.

II. PROBLEM FORMULATION

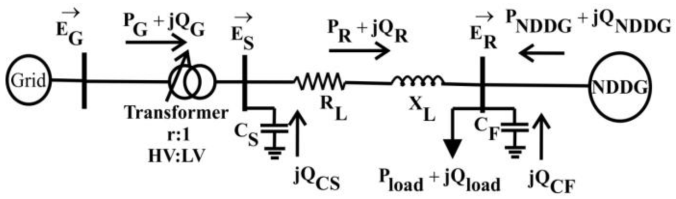

Fig.1(a). Grid connected system with DFIG as NDDG.

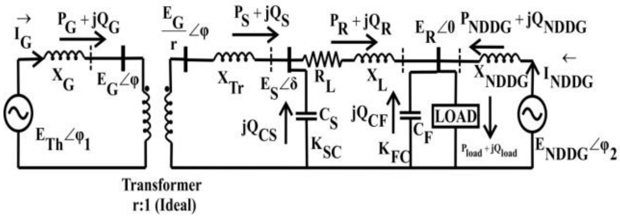

Fig.1(b). Grid connected system with DDG.

In this paper, the issue formulation is based on a simple radial distribution system, as shown in Fig. 1. The NDDG's reactive power schedule is determined by grid conditions, but the active power dispatch schedule is determined by system operators. The ULTC is positioned on the high voltage side of the transformer, which regulates the total voltage of the distribution feeder. The SCs are located on both the sending and receiving ends. These are a set of independently controlled unit capacitors connected in parallel. Since ULTC and SCs regulate distribution feeder voltages up to a small percentage of the rated value, the NDDG can absorb or supply the required amount of reactive power. The transformer's power loss is small for numerical simplicity.

After several simplifications and basic circuit analysis, the sending and receiving end voltages can be written as follows:

$$E_S = f_1(tap, K_{SC}, K_{FC}, Q_{NDDG}) \quad (1)$$

$$E_R = f_2(tap, K_{SC}, K_{FC}, Q_{NDDG}) \quad (2)$$

the objective function is formulated as:

$$J = \sum_{h=1}^{H-1} \begin{pmatrix} CP_{Loss} E[P_{Loss}^h] + C_{tap}|tap^{h+1} - tap^h| + C_{SC}|k_{SC}^{h+1} - k_{SC}^h| \\ + \sum_{n=1}^{N} C_{FC}|k_{FCn}^{h+1} - k_{FCn}^h| \end{pmatrix} \quad (3)$$

where the following is a definition of the control variables:

$$u_h = \{tap^h, K_{SC}^h, k_{FC1..N}^h, V_{NDDG1...S}^h\} \quad (4)$$

Subjected to the following constraints:

$$V_{min} \leq V_b^h \leq V_{max} \quad (5)$$

$$pf_{min} \leq pf_{DGs}^h \leq 1 \quad (6)$$

$$tap_{min} \leq tap^h \leq tap_{max} \quad (7)$$

$$0 \leq K_{SC}^h \leq K_{SC,max} \quad (8)$$

$$0 \leq K_{FCn}^h \leq K_{FCn,max} \quad (9)$$

h=1,2,3…………….H, b=1,2,3…B and n=1,2………N.

III. Load forecasting and DFIG output power forecasting

To estimate DFIG output power using the ANFIS model, eight elements are considered based on their importance and influence. Figure 3 shows the ANFIS structure.

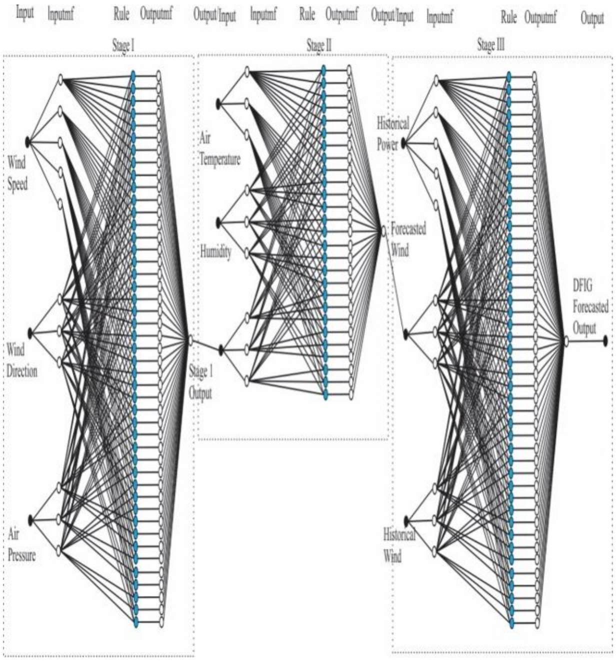

Fig.3 ANFIS model for predicting DFIG output power.

Predictability is an important factor in determining power system efficiency. If the prognosis is overblown, it is feasible to start too many units with too much reserve. Additionally, production prices have risen. Furthermore, it adds to the development of excess power, which wastes significant investments. Underestimated forecasts, on the other hand, can be dangerous. Unmet demand and operation both contribute to insufficient spinning reserve preparation.

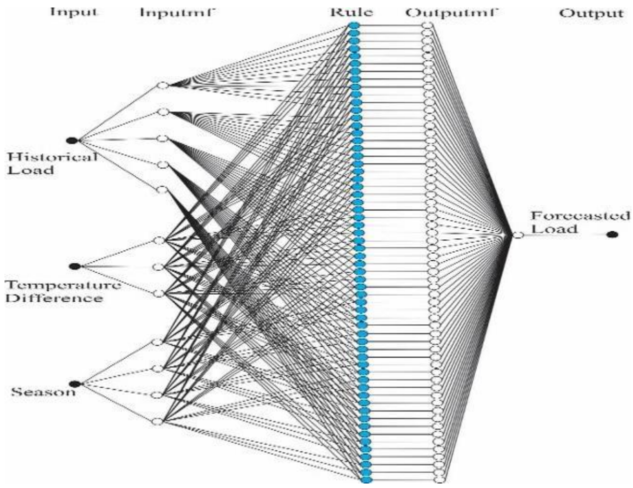

Fig.4 ANFIS model for predicting Load power.

IV. Coordination of reactive power with the particle swarm optimization technique

Step 1: Generate initial positions of X_i^0 and respective velocities Y_i^0 randomly, Load test system data

Generate initial positions of X_i^0 and respective velocities Y_i^0 randomly for $i = 1,2,3 \ldots \ldots n.$ forecast the load using ANFIS model and maximum number of iterations (K_{max}), Load test system data, i.e., is scheduled real power generation and maximum available reactive power of NDDG and Load of the test system.

Step 2: Assume initial conditions that are required for power flow calculations

Assume bus voltage magnitudes equal to one and respective angles equal to zero, power loss equal to zero initially for all h, b, s.

Step 3: Calculation of reactive power injected by the shunt capacitors

The reactive power injected by the shunt capacitors is calculated with the initial values specified in step 1 and step 3 using the equations (10) and (11) for all h, b.

$$Q_{CS} = K_{SC}\,\omega C_S E_S^2 \approx K_{SC}\, Q_{unitCS,rated} \quad (10)$$

$$Q_{CF} = K_{FC}\,\omega C_F E_R^2 \approx K_{FC}\, Q_{unitCF,rated} \quad (11)$$

Step 4: Calculation of bus currents

Calculate the bus currents starting from the end buses of all branches to the slack bus of the main feeder using the equation (12).

$$\tilde{I}_b^h = \left(\frac{\left(s_{Lb}^h - s_{Dgs}^h\right)}{\tilde{v}_b^h}\right)^* + \sum_{m \in M} \tilde{I}_m^h \quad for\ all\ h, b, m \quad (12)$$

Step 5: Check voltage mismatch condition

Determine the voltage mismatch using the equation (13) and check voltage mismatch using the equation (14); if satisfied, go to the next step; otherwise, go to step 3.

$$\left|\Delta\tilde{V}_b^{h,w}\right| = \left|\tilde{V}_b^{h,w}\right| - \left|\tilde{V}_b^{h,w-1}\right| \quad (13)$$

$$\left|\Delta\tilde{V}_b^{h,w}\right| < \varepsilon_b^h \quad (14)$$

Step 6: Check the NDDG bus voltage mismatch condition

Determine the voltage mismatch at NDDG buses using the equation (15) and check voltage mismatch using the equation (16); if satisfied, go to step 9; otherwise go to next step.

$$\left|\Delta V_{NDDGs}^{h}\right| = \left|V_{NDDGs,specified}^{h}\right| - \left|V_{NDDGs,calculated}^{h}\right| \quad (15)$$

$$\left|\Delta V_{NDDGs}^{h}\right| < \varepsilon_{NDDGs}^{h} \quad (16)$$

Step 7: Update the NDDG reactive power

Calculate the updated value of NDDG reactive power using the equations (17) and (18).

$$\Delta Q_{NDDGs}^{h} = H^{-1}\Delta V_{NDDGs}^{h} \quad (17)$$

$$Q_{NDDGs,new}^{h} = Q_{NDDGs,old}^{h} + \Delta Q_{NDDGs}^{h} \quad (18)$$

Where H is the sensitivity matrix.

Step 8: Check the reactive power constraint of NDDG

Check the reactive power of NDDG updated in step 7 is within the limits or not using the equation (19). If satisfied, calculate the reactive power of NDDG using equation (20); otherwise, calculate the reactive power of NDDG using equation (21).

$$Q_{NDDGs,min}^{h} \le Q_{NDDGs,new}^{h} \le Q_{NDDGs,max}^{h} \quad (19)$$

$$Q_{NDDGs}^{h} = Q_{NDGs,new}^{h} \quad (20)$$

$$Q_{NDDGs}^{h} = max\left(min\left(Q_{NDDGs,new}^{h}, Q_{NDDGs,max}^{h}\right), Q_{NDDGs,min}^{h}\right) \quad (21)$$

Step 9: Stop the power flow calculation and return the real power loss of distribution system, voltage magnitudes of buses and calculated voltages of NDDGs.

Step 10: Adjustment of initial positions of X_i^0

Initial values of X_i^0 are adjusted to meet the voltage constraint represented in equation (22).

$$V_{min} \le V_b^h \le V_{max} \quad (22)$$

Step 11: Calculation of fitness function and update P_i^k and G^k

Calculate the fitness function using the equation (23) and update P_i^k and G^k with adjusted values of X_i^0.

$$J = \sum_{h=1}^{H-1}\left(\begin{array}{c} CP_{Loss}E\left[P_{Loss}^{h}\right] + C_{tap}\left|tap^{h+1} - tap^{h}\right| + C_{SC}\left|k_{SC}^{h+1} - k_{SC}^{h}\right| \\ + \sum_{n=1}^{N} C_{FC}\left|k_{FCn}^{h+1} - k_{FCn}^{h}\right| \end{array}\right) \quad (23)$$

Step 12: Update X_i^k and P_i^k

After the evolution of fitness function then update the values of X_i^k and P_i^k using the equations (24) to (26).

$$Y_i^{k+1} = \left(\begin{array}{l} round\left(w \cdot Y_i^k\right) + round\left(\begin{array}{c} c_1 \cdot rn(0,1) \cdot \\ \left(P_i^k - X_i^k\right) \end{array}\right) + \\ round\left(c_2 \cdot rn(0,1) \cdot \left(G^k - X_i^k\right)\right) \end{array}\right) \quad (24)$$

$$w = w_{\max} - \left(w_{\max} - w_{\min}\right) \times \frac{k}{k_{\max}} \quad (25)$$

$$X_i^{k+1} = X_i^k + Y_i^k \quad (26)$$

Step 13: Calculation of reactive power injected by the shunt capacitors

The reactive power injected by the shunt capacitors is calculated with the updated values obtained from step 12 for all h, b.

Step 14: Calculation of bus currents

Calculate the bus currents starting from the end buses of all branches to the slack bus of the main feeder using the equation (27).

$$\tilde{I}_b^h = \left(\frac{\left(S_{Lb}^h - S_{Dgs}^h\right)}{\tilde{V}_b^h}\right)^* + \sum_{m\in M}\tilde{I}_m^h \quad for\ all\ h,b,m \quad (27)$$

Step 15: Check voltage mismatch condition

Determine the voltage mismatch using the equation (28) and check voltage mismatch using the equation (29); if satisfied, go to the next step; otherwise, go to step 13.

$$\left|\Delta\tilde{V}_b^{h,w}\right| = \left|\tilde{V}_b^{h,w}\right| - \left|\tilde{V}_b^{h,w-1}\right| \quad (28)$$

$$\left|\Delta\tilde{V}_b^{h,w}\right| < \varepsilon_b^h \quad (29)$$

Step 16: Check the NDDG bus voltage mismatch condition

Determine the voltage mismatch at NDDG buses using the equation (30) and check voltage mismatch using the equation (31); if satisfied, go to step 19; otherwise go to next step.

$$\left|\Delta V_{NDDGs}^{h}\right| = \left|V_{NDDGs,specified}^{h}\right| - \left|V_{NDDGs,calculated}^{h}\right| \quad (30)$$

$$\left|\Delta V_{NDDGs}^{h}\right| < \varepsilon_{NDDGs}^{h} \quad (31)$$

Step 17: Update the NDDG reactive power

Calculate the updated value of NDDG reactive power using the equations (32) and (33).

$$\Delta Q_{NDDGs}^{h} = H^{-1}\Delta V_{NDDGs}^{h} \quad (32)$$

$$Q_{NDDGs,new}^{h} = Q_{NDDGs,old}^{h} + \Delta Q_{NDDGs}^{h} \quad (33)$$

Where H is the sensitivity matrix

Step 18: Check the reactive power constraint of NDDG

Check the reactive power of NDDG updated in step 17 is within the limits or not using the equation (34). If satisfied, calculate the reactive power of NDDG using equation (35); otherwise, calculate the reactive power of NDDG using equation (36).

$$Q_{NDDGs,min}^{h} \le Q_{NDDGs,new}^{h} \le Q_{NDDGs,max}^{h} \quad (34)$$

$$Q_{NDDGs}^{h} = Q_{NDDGs,new}^{h} \quad (35)$$

$$Q_{NDDGs}^{h} = max\left(min\left(Q_{NDDGs,new}^{h}, Q_{NDDGs,max}^{h}\right), Q_{NDDGs,min}^{h}\right) \quad (36)$$

Step 19: Stop the power flow calculation and return the real power loss of distribution system, voltage magnitudes of buses and calculated voltages of NDDGs.

Step 20: Check the fitness function condition and iteration condition

Check the fitness function is satisfied or not using the equation (37) and check iterations equal to maximum number of iterations using the equation (38). if these two conditions are satisfying then stop the procedure and return power loss, voltages at all buses and reactive power supplied or absorbed by NDDG. Otherwise, increase iteration by one and then repeat steps from 11 to 20.

$$J^K - J^{K-1} < \varepsilon \quad (37)$$

$$K \ge K_{max} \quad (38)$$

Step 21: Calculation of Steady-State Voltage Fluctuations (SSVF)

Calculate SSVF using the equation (39) with the voltages updated in step 20.

$$SSVF = \frac{1}{B}\sum_{b=1}^{B}\left(\sum_{h=1}^{H-1}\left|V_b^{h+1} - V_b^h\right|\right) \ for\ all\ values\ of\ b,h \quad (39)$$

V. CASE STUDY & RESULTS

proposed technique was tested on the 10kV 16 bus system illustrated in Figure 5, which included two 3MW DFIGs distributed across many locations, as well as ULTC and SCs. Figure 6 shows the output patterns of 3MW DFIGs. Based on the location of DFIGs, the results are classified into three cases:

Case: I

Two 3MW DFIGs were connected to different locations on different feeders (bus 5 on feeder 1 & bus 8 on feeder 2;). Figure 5 shows a comparison of power loss and switching loss using traditional and PSO approaches.

The reactive power support two 3MW DFIGs decreased SSVF, power loss, switching loss, and total loss, as demonstrated in Table 1

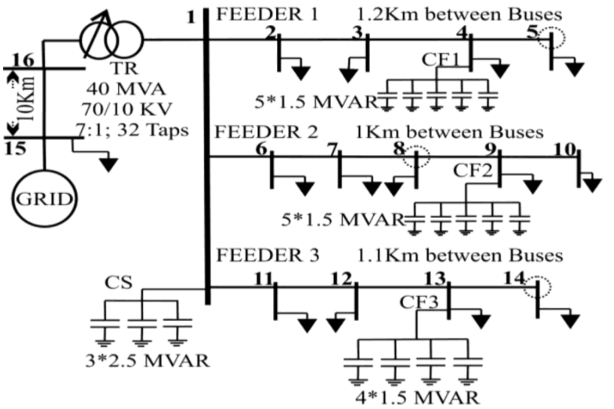

Fig.5. Grid-connected 10kV practical system single line diagram.

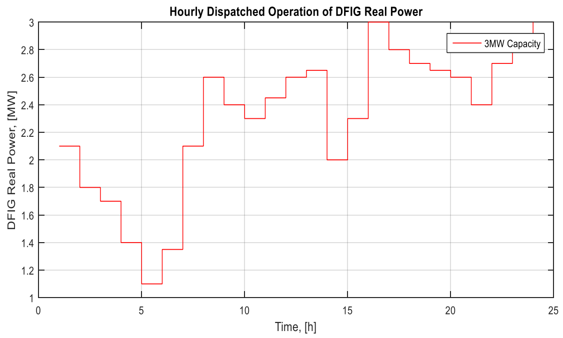

Fig.6. Forecasted output power for 3MW DFIG using the ANFIS model.

Table.1. 3MW DFIGs positioned at bus 5 and at bus 8

Control Methods		Conventional Method	PSO Method
Power loss (MWh)		12.4011	8.22017
SSVF(%)		0.260398	0.221052
SONs of VCDs	ULTC	5	2
	SC	0	9
	FC1	13	7
	FC2	9	7
	FC3	8	3
Power loss ($)		992.088	657.6136
Switching loss ($)		1600	1380
Total loss ($)		2592.088	2037.6136
Comparison (%)			
Control Methods / Performance Parameters			PSO & Conventional
Power loss reduction			33.714187
Switching loss reduction			13.75
SSVF reduction			15.109947
Total loss reduction			21.391033

From table 1, it is clear that the proposed PSO method effectively achieving the objective by reducing the power loss by 33.71%, switching loss by 13.75%, SSVF by 15.10% and Total loss by 21.39% when compared with conventional method.

Case: II

Two 3MW DFIGs were connected to different locations on different feeders (bus 8 on feeder 2 & bus 14 on feeder 3). Figure 5 shows a comparison of power loss and switching loss using traditional and PSO approaches.

The reactive power support two 3MW DFIGs decreased SSVF, power loss, switching loss, and total loss, as demonstrated in Table 2

Table.2. 3MW DFIGs positioned at bus 8 and at bus 14

Control Methods		Conventional Method	PSO Method
Power loss (MWh)		12.4439	9.6733
SSVF(%)		0.262914	0.253246
SONs of VCDs	ULTC	3	0
	SC	0	10
	FC1	13	8
	FC2	9	7
	FC3	8	3
Power loss ($)		995.512	773.864
Switching loss ($)		1440	1320
Total loss ($)		2435.512	2093.864
Comparison (%)			
Control Methods / Performance Parameters			PSO & Conventional
Power loss reduction			22.264724
Switching loss reduction			8.3333333
SSVF reduction			3.6772481
Total loss reduction			14.027769

From table 1, it is clear that the proposed PSO method effectively achieving the objective by reducing the power loss by 22.26%, switching loss by 8.33%, SSVF by 3.67% and Total loss by 14.02% when compared with conventional method.

Case: III

Two 3MW DFIGs were connected to different locations on different feeders (bus 14 on feeder 3 & bus 5 on feeder 1). Figure 5 shows a comparison of power loss and switching loss using traditional and PSO approaches.

The reactive power support two 3MW DFIGs decreased SSVF, power loss, switching loss, and total loss, as demonstrated in Table 3.

From table 1, it is clear that the proposed PSO method effectively achieving the objective by reducing the power loss by 12.57%, switching loss by 30.26%, SSVF by 21.33% and Total loss by 23.06% when compared with conventional method.

Table.3. 3MW DFIGs positioned at bus 14 and at bus 5

Control Methods		Conventional Method	PSO Method
Power loss (MWh)		13.0208	11.3838
SSVF(%)		0.280961	0.221014
SONs of VCDs	ULTC	4	0
	SC	0	9
	FC1	13	6
	FC2	9	4
	FC3	8	3
Power loss ($)		1041.664	910.704
Switching loss ($)		1520	1060
Total loss ($)		2561.664	1970.704
Comparison (%)			
Control Methods / Performance Parameters			PSO & Conventional
Power loss reduction			12.572192
Switching loss reduction			30.263158
SSVF reduction			21.336413
Total loss reduction			23.06938

VI. CASE STUDY & RESULTS

In this paper load and DFIG powers are forecasted one day in advance for scheduling the reactive power of ULTC and SCs for reducing the switching operations of ULTC and SCs. The objectives of this paper are reduction of SOs, power loss and SSVF. To achieve these objectives, this paper proposed PSO method for reactive power coordination between two 3MWs DFIGs, ULTC and SCs. The proposed method is tested on 10kv south Korean distributed system in matlab and compared with conventional method. from the findings, it is clear that the proposed method effectively reducing the switching operations of ULTC and SCs, power loss and SSVF when compared with conventional method irrespective of location of DFIGs.

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