Predictive Var Management of Distributed Generators

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Abstract— **This paper presents and describes a smart predictive technique for managing reactive power from a numbers of distributed generation (DG) units connected to low voltage (LV) buses in a distribution network. The technique applies an optimization process in the first stage and in the second stage the procedure is generalized using artificial neural network (ANN). The ANN is trained to replace the role of optimization process which is repetitive in nature and time consuming. The technique can speed up the time while scarifying a little accuracy. The objective is to develop an intelligent management tool that can be used to manage reactive power from a group of DG units for online management. This technique predicts the optimal reactive power fro the next time step that needs to be supplied by each DG unit with the objective of minimizing active power losses and keeping the voltage profile within the required limit. The effectiveness of the method is tested by predicting reactive power from twelve DG units simultaneously and the result is promising. Intelligent management technique presented in this paper is suitable to be integrated into online management scheme under Smart Grid concept.**

Keywords- Distributed Generation, Online Management, Optimal Reactive Power, Neural Networks, Smart Grid.

I. INTRODUCTION

Due to economic, technical and environmental benefits, distributed generation (DG) concept was introduced a decade ago into the distribution network to supply a part of the customer loads. It is expected that in the coming years, DG units will supply up to 40% of the distribution network's load demand. Also to achieve a Smart Grid [1], a large number of DG units must be integrated inside distribution network. These large number of DG units will be required to technically support the network during steady state operation as well as during critical times. The technical benefits offered by DG application in low voltage (LV) distribution network are power loss reduction and provide voltage support [2]. Keeping power losses at minimum is one of the features of future electricity networks under Smart Grid concept.

The power loss will be reduced even if DG units only supplying active power to the consumer. This is because of the fact that the upstream network needs less energy to be transferred where loads can support part of their own energy needs. Further loss reduction can be achieved if reactive power is also allowed to supply by DG units for voltage regulation. Even though DG has the capability of supplying reactive power, this advantage is restricted by current grid code due to lack of experience and fear to allow this new ancillary service. The main issue is that the DG units will interfere with the existing voltage control scheme and it may unexpectedly results in system instability. Furthermore most of the installed DG units are owned by the consumers where utility does not have a control on the operation of these units. In the future however, this restriction is expected to be removed and the DG units will be controlled centrally by the utility. This vision will bring the expectation of DG to participate in improving the security, reliability and quality of electricity supply by providing ancillary services.

There are a number of publications discussing and proposing methods for managing reactive power from DG units. For example in [3], reactive power from DG units is coordinated locally with local voltage controller due to poor communication infrastructure in the distribution network. In this method, there is no coordination among DG units and voltage control devices are located remotely. However, under the concept of Smart Grid [1], advance communication facilities will be integrated into the network. With the existence of good communication facilities, DG units are suggested to be coordinated with other voltage control devices [4]. In [5] evolutionary optimization technique is used to determine the optimal reactive power from DGs while coordinating the operating points of each individual voltage controller. However, since the voltage profiles in the network changes every time with varying loading condition, the performance of the optimization is computationally expensive. This limits the proposed technique for real time online application as required in a Smart Grid concept. In addition, complete system information is needed in carrying out such optimization simulation.

To overcome the repetitive task of optimization algorithm, Artificial Neural Network (ANN) was introduced in [6] to replace the optimization task which manages the DG unit operation. The objective was to reduce operational cost of DG unit subjected to fuel and electricity tariff. The ANN was trained using database extracted from genetic algorithm optimization process and the results given by ANN were shown to be comparable with the results given by genetic algorithm.

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However, in the study, the ANN implementation was only for one DG unit.

In this paper, an intelligent predictive management technique for a group of DG units which is suitable for on line application is presented. An ANN is trained to replace the task of optimization process and it is used to predict the next time step optimal output of reactive power from a group of DG units. The management objective is to minimize power losses while maintaining voltage profile throughout the distribution network within the required limits. This fast and promising technique eliminate repetitive and time consuming process of optimization simulation which has to be performed everytime the network loading condition changes. This technique is suitable to integrate into the energy management system under Smart Grid concept.

The next section of this paper will first envision future distribution network operation and control issues. DG's reactive power supplying capability is then briefly discussed. Development procedure of intelligent predictive management technique for online application is then described. Finally the testing of proposed technique is demonstrated and the results are discussed.

II. CONCEPTUAL FUTURE DISTRIBUTION NETWORK

Future distribution network is a smart grid which will be integrated with advance communication facilities linking all DGs, sensors and actuators with network control center as depicted in Fig. 1. In this network, power and information flows are assumed to be in real time. This will enable efficient decisions on how to operate the network in real time. Network will be scanned by data acquisition devices in every 15 minutes thus in 24 hours operation, the network will be scanned for 96 times. Acquired information will be used to determine the optimal operation of all DG units and the voltage controllers in the next time step. It is envision that all voltage controllers and DGs inside distribution network will be coordinated and controlled remotely by a control center. Optimal setpoints will be calculated and adjusted remotely through communication link in every 15 minutes.

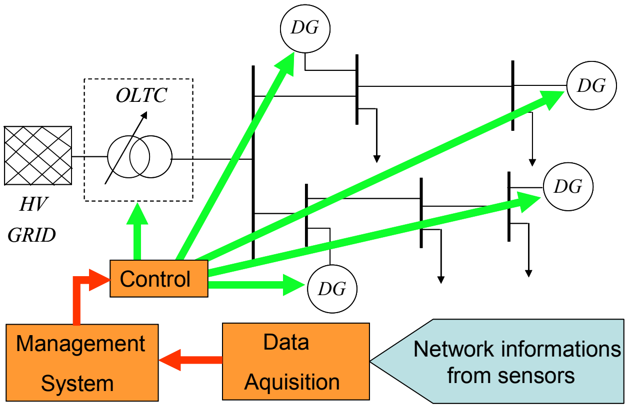


Figure 1. Future distribution network

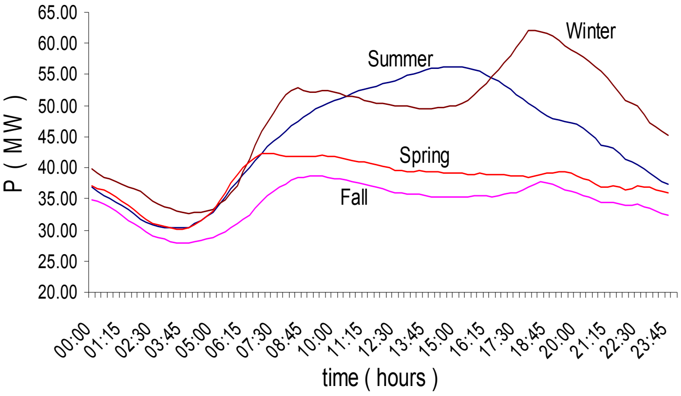


Figure 2. Typical load demand curve

As mentioned earlier, voltage profile of the distribution network, varies with load demand and follows human activities according to the time of the day and season of the year. A typical load demand curve is depicted in Fig. 2 for a working day in summer, winter, fall and spring. A peak load in winter season is nearly doubles the peak load in fall. During light load, voltage will rise and in contrast decrease during heavy load condition. A voltage control scheme will try to keep the voltage within its voltage constraint following the changes of load demand. A voltage control scheme works conventionally based on local measurement and is usually operated independently.

Conventionally, primary voltage controller is a transformer equipped with online load tap changer (OLTC) at the main substation and capacitor banks distributedly located inside the network. Based on local voltage measurement at the substation feeder, taps of the transformer is changed to return the voltage within specified range around the reference value which is usually slightly about the nominal value. Capacitor banks are used to supply reactive power for voltage regulation at the connected node. These capacitors are switched in and out using voltage regulating relay to deliver reactive power in steps. The switching however lower the power quality in the network as it leads to step changes of the voltage. Eventhough this power quality problem can be reduced by switching smaller amount of capacitance at each step, this method increase maintenance cost of switchgear and complexity of control equipments.

In future distribution networks, due to coordination of OLTC with other voltage control devices including DGs, the conventional control method are seemed not suitable. As the objective of conventional OLTC control is to return the voltage inside deadband range, transformer's tap will probably positioned unoptimally. It is therefore recommended that tap position on substation transformer is forced to an optimal position remotely by control center. Capacitor banks probably will be removed from the network as its voltage regulation task can be replaced by DG units.

Future distribution network which is termed smart, need to be efficient where active power losses is kept at minimum. This power loss depends on magnitude of the current flows through the resistance of the line. Subjected to the number of lines available in the network, total active power losses is given by

$$P_{total}^{loss} = \sum_{ij} 3I_{ij}^2 R_{ij} \qquad \forall ij \in N_L \tag{1}$$

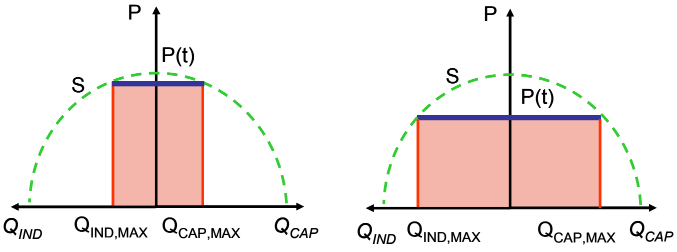
where N_L is the number of the lines available in the network. In a ac distribution line due to electric field and magnetic field developed as a results of time varying current flow, reactive power which transmit no energy is produced. Reactive current flow in the line contributes to extra power losses in addition to active power losses mentioned previously. These losses can be minimized by efficiently coordinating reactive power from DG and other voltage controlled devices in the network. This loss reduction in distribution level will also reduce the losses in transmission network. This will lead a reduction of fossil fuel combustion, air pollutant and green house gases. The need for providing spinning reserves can also be reduced.

III. REACTIVE POWER FROM DG

DG unit connected to electrical grid through power electronic converter can be set to inject reactive power by changing its operating power factor or increasing its reactive current output. Its maximum reactive power that can be supplied is given by

$$Q_{DG,max}(t) = \sqrt{S_{DG,MAX}^2 - P_{DG}^2(t)} \tag{2}$$

How much reactive power can be supplied by a particular DG unit depends on its active power setpoint. The diagram illustrating reactive power capability is shown in Fig. 3. If the DG active power is set close to its rated apparent power rating, capacitive or inductive reactive power range that can be supplied is small (Fig. 3(a)). Reactive supply capability of DG can be increased by reducing its active power generation (Fig. 3(b)). If active power setpoint is reduced, more reactive supply is guaranteed. In this case, active power output has to be curtailed which is not favorable to the economic point of view because active power from DG is expected to be cheaper than transported active power from upstream. But if this action can benefit the distribution network operation, this active power curtailment is acceptable. In some cases, DG can be intentionally oversized to increase its power supply capability. Active power supply can be set at rated value of DG while at the same time there is still reactive power available up to its oversized rating.



(a) (b)

Figure 3. Apparent, active and reactive power from DG
(a) DG reactive capability with high active power setpoint
(b)DG reactive capability with lower active power setpoint

By allowing DG to inject reactive power, the dependency of the distribution system on the reactive power from high voltage grid is reduced. Eventhough the amount of reactive power that can be supplied by the DG is limited and is not enough to supply the entire reactive power requirement; this corrective action in consequence can minimize the power losses inside the distribution network. As DGs will be distributed and integrated inside distribution network, depending on the location, reactive power amount required from each DG unit will be different for different operating condition. Too much reactive power requested will limit its active power generation but too low reactive power supply will probably be not enough to regulate the voltage at the connection points. Optimal reactive power should be calculated because this information can be used to determine how much reactive power should be provided by each DG unit. To find optimal reactive power, optimization algorithm is required.

IV. OPTIMIZATION AND GENERALIZATION PROCEDURE

In the distribution network which contain transformer with OLTC and DG units, transformer taps and reactive power from each DG units can be treated as control variables. For solving DG optimal reactive power, the problem is mathematically formulated as follows:

Min $\qquad P_{loss}(\boldsymbol{x})$
Subject to

a) Transformer tap setting limits
$$a^{\min} \le a \le a^{\max} \tag{3}$$
b) All bus voltage limits
$$u_i^{\min} \le u_i \le u_i^{\max} \qquad \forall i \in N_B \tag{4}$$
c) DG reactive power limits
$$Q_{DG\_i}^{\min} \le Q_{DG\_i} \le Q_{DG\_i}^{\max} \qquad \forall i \in N_{DG} \tag{5}$$

where a is the transformer tap, N_B is the number of buses and N_{DG} is the number of DG units. Vector $\boldsymbol{x}$ contains control variables (3) and (5). The transformer tap setting, a is treated as a discrete decision variable while the DG reactive power limit, Q_{DG} is treated as a continuous decision variable.

In order to achieve optimal operation condition, optimization process has to be performed for every change in load demand. However, running optimization simulation is timely expensive and therefore it is not suitable for real time online management application envision in Smart Grid. Moreover complete information of the network is required to carry out such optimization process. The results of optimization however can be generalized by using ANN.

Information from database created from the optimization simulation can be used to train the ANN offline. The ANN [11] can be trained by introducing the inputs of:

- Active power draws by distribution network at current time step and previous h time steps
- f time steps ahead of forecasted load demand
- Active power from N number of DG

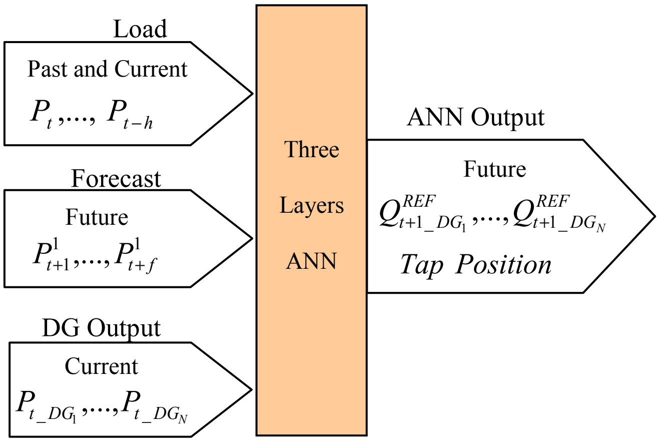


Figure 4. ANN implementation for predicting DG reactive power

The output of ANN is a vector comprising of the optimal reactive power of each DG and tap position of main substation transformer. Implementation of the said ANN is depicted graphically in Fig. 4. In the ANN controller development, *h* time steps of historical active power draws by distribution network, *f* time steps of future forecasted load demand and active power output from all units of DG can be used. To make sure ANN controller is robust in predicting optimal reactive power, during the training process it should also be introduced with the input data with has forecast errors. Active power from DG can also be an input if some DG is operated at a certain power factor while some are intentionally oversized.

V. TEST SYSTEM AND RESULTS

The proposed online predictive technique is applied to the distribution network shown in Fig. 5. This radial distribution network is fed by a HV grid through main substation transformer which steps down the 110 kV voltage to 10 kV medium voltage. There are three feeders branching out from the substation with each feeder having three, four and five 10kV/0.4kV distribution transformers, respectively. On each LV side of a distribution transformer there are aggregated DGs with rating capability of 33% of the maximum local load. With this magnitude of generation capacity all the active power supplied by DGs is consumed by local load. In this distribution network, the main substation transformer is equipped with OLTC while all the other distribution transformers are equipped with off load tap changers. Without DG reactive supply, the main voltage control in the network is achieved by using OLTC at the main substation.

DG technology considered in the study is converter based DG in which generation can be controlled by setting its power set point values remotely. DG technologies that fit this requirement for example are microturbine generation system and fuel cell. These two technologies are already available commercially and are the most prospective power generators for distributed generation application. These two technologies can be used to generate both electricity and thermal power, but in this study it is assumed that they are used to generate only electrical power. All DG units are also assumed to be intentionally oversized to reduce the complexity.

In creating a database, optimization simulation is run for each 96 time steps of distribution network operation based on the historical load demand [7]. The load is distributed at each time step. Optimal reactive power from each DG units, transformer tap position and, network power losses and others information are saved in the database. An adaptive particle swarm optimization (APSO) [8-9] is utilized as an optimization algorithm. APSO is a parameter free algorithm which is able to find global optimal solution by the process motivated by social behavior of swarm such as fishes and birds searching for food. This APSO is integrated into power flow program winlf8 [10].

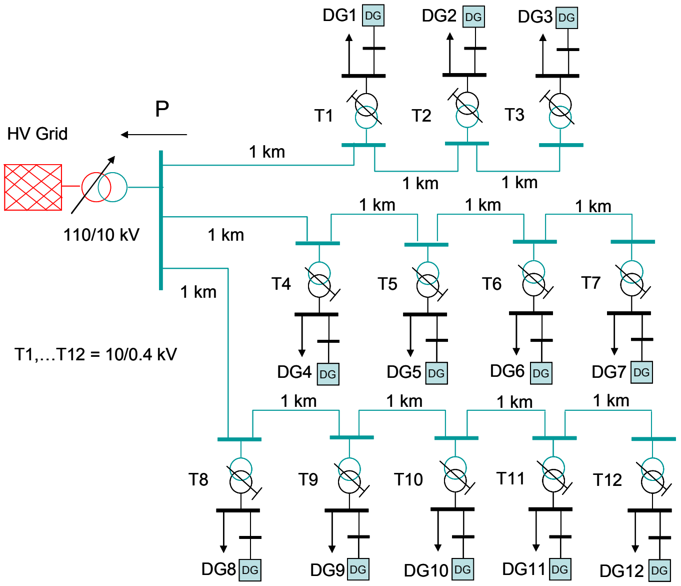


Figure 5. Distribution network integrated with DG

In the ANN controller development, six time steps of historical active power draws by distribution network, six time steps of future forecasted load demand, and active power output from all DG units are used as inputs. To make sure the ANN [11] is robust in predicting optimal reactive power and transformer tap position, during the training process, it is introduced with three sets of input data with has forecast error of zero, two and five percent respectively.

The performance of the ANN is evaluated in terms of maximum error ($e_{\max}$) and RMS error (e_{rms}) which are given respectively as,

$$e_{\max} = \max\{|T_q - O_q|\}, \quad q = 1,2,\ldots,NO \tag{6}$$

$$e_{rms} = \sqrt{\frac{1}{p^{\max}} \sum_{q=1}^{p^{\max}} \frac{1}{NO} \sum_{q=1}^{NO} \left[t_{qp} - o_{qp}\right]^2} \tag{7}$$

where $T_q = [t_{q1}, t_{q2},\ldots, t_{qp}^{max}]$ is the target vector at the q^{th} neuron of the output layer, $O_q = [o_{q1}, o_{q2},\ldots, o_{qp}^{max}]$ is the output vector at the q^{th} neuron of the output layer, p^{max} is the number of patterns and NO is the number of neurons in the output layer.

The ANN controller is tested to predict the optimal reactive power for 96 new time steps of one day operation which was not introduced during the training process. Maximum error (e_{max}), root mean square error (e_{rms}) and standard deviation of error are calculated and tabulated in Table 1. The results show that the trained ANN is correctly predicted all the optimal DG reactive power with small errors. Maximum prediction error is seen for DG 2 with the magnitude of 0.0804 MVar. The greatest root mean square error as can be seen is for DG 4 with the value of 0.0159 MVar. Standard deviations of error for all DG units are closed to their root mean square errors.

TABLE I. PERFORMANCE OF ANN IN TESTING STAGE

DG No.	e_{max} (MVar)	e_{rms} (MVar)	σ (MVar)
DG 1	0.0348	0.0086	0.0085
DG 2	0.0804	0.0117	0.0118
DG 3	0.0501	0.0124	0.0125
DG 4	0.0636	0.0159	0.0160
DG 5	0.0411	0.0107	0.0107
DG 6	0.0286	0.0089	0.0089
DG 7	0.0541	0.0127	0.0127
DG 8	0.0261	0.0097	0.0098
DG 9	0.0484	0.0122	0.0123
DG 10	0.0351	0.0097	0.0098
DG 11	0.0318	0.0094	0.0094
DG 12	0.0586	0.0117	0.0117

The reactive powers predicted by ANN are compared graphically with the values obtained from the conventional optimization technique in Figs. 6 and 7 for DG 4 and DG 12 respectively. Customer oriented system is used in the simulation where negative reactive power is capacitive while positive value is inductive. From the results display in both Figs.6 and 7, it can be seen that to meet the active power loss minimization objective in some time steps, DG 12 needs to supply capacitive reactive power to the network while DG 4 needs to inject inductive reactive component. These requirements are dictated by the location of the DG units in the network. For example the farthest location in the network is where DG 12 is located. This location experience the lowest voltage profile compared to the other locations. In Fig. 8, voltage correction provided by OLTC is shown. These voltage corrections represent the position of its tap. The value given by ANN is continuous so the values are rounded to the nearest discrete values. It can be seen that ANN manages to predict the position of the taps without any error.

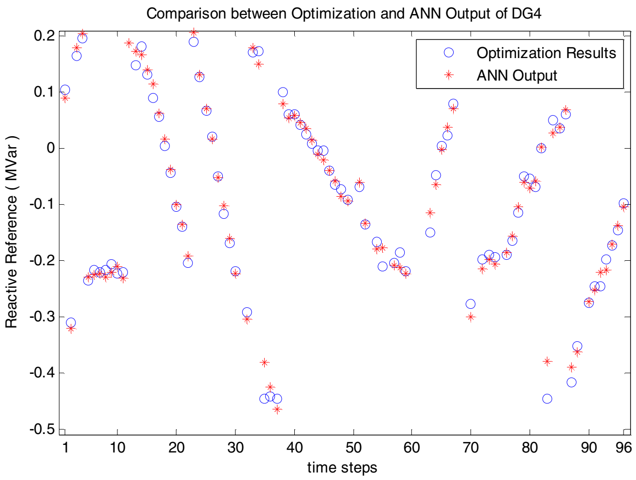


Figure 6. Reactive power reference for DG 4

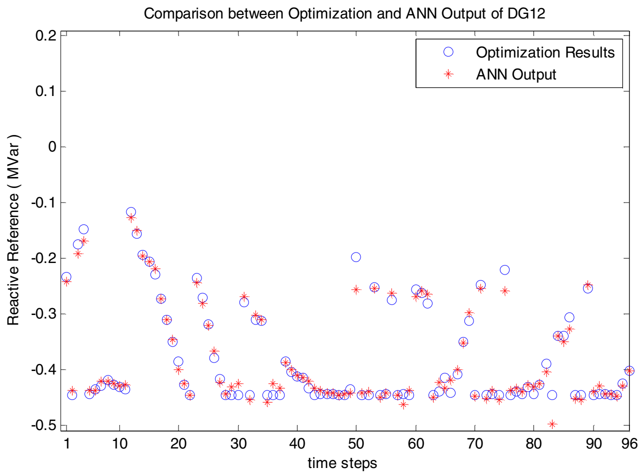


Figure 7. Reactive power reference for DG 12

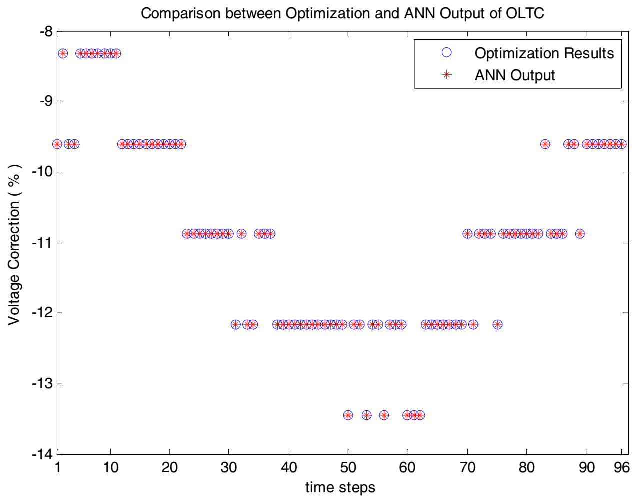


Figure 8. Voltage correction provided by OLTC

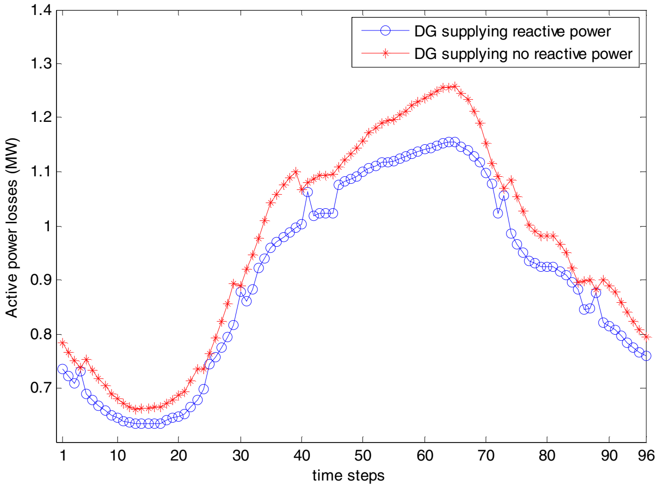


Figure 9. Comparison of active power losses

As the main objective is to centrally manage a group of DG units to reduce the active power losses, the comparison of active power losses with and without reactive power supply coming from DG is depicted in Fig. 9. In most of the time steps shown in the figure, at least 0.05 MW of active power losses are reduced when reactive power form DG is centrally managed. In some time steps, it can be seen that up to 0.1 MW of loss reduced is achievable. If all losses are accumulated, a substantial amount of reduction in active power losses could be achieved in one day operation. It also has to be kept in mind that this loss reduction in distribution network will also reduce the losses in the transmission network as well. If all distribution networks connected to transmission grid manage its DG reactive power effectively, a substantial amount of losses could be reduced in the whole power system.

VI. CONCLUSION

In this paper, intelligent predictive control technique for online management of reactive power from a group of DG units is presented. A group of DG units is centrally controlled using one controller which was developed using two stage intelligent techniques APSO and ANN. The database extracted from APSO optimization is used to train an ANN to predict the next time step optimal reactive power from each DG. The ANN replaced the task of optimization process in finding the optimal operating point of each DG available in the network. The effectiveness of the technique is demonstrated on the test distribution network containing twelve DG units. The simulation results indicate that a single ANN is effective in predicting the optimal reactive power from twelve DG units simultaneously with acceptable error and OLTC position without any error. The number of tap changes is also considered acceptable. This predictive control technique is suitable to be integrated into energy management system application under smart grid concept which will be applied to the Europe's electricity networks in coming years. In addition to effective management of reactive supplies from DGs, voltage control of the distribution network is performed simultaneously.

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