Fuzzy Logic Based Coordinated Voltage Control for Distribution Network with Distributed Generations

T. Juhana Hashim and A. Mohamed

Abstract**—**This paper discusses the implementation of a fuzzy logic based coordinated voltage control for a distribution system connected with distributed generations (DGs). The connection of DGs has created a challenge for the distribution network operators to keep the voltage in the system within its acceptable limits. Intelligent centralized or coordinated voltage control schemes have proven to be more reliable due to its ability to provide more control and coordination with the communication with other network devices. In this work, voltage control using fuzzy logic by coordinating three methods of control, power factor control, on load tap changer and generation curtailment is implemented on a distribution network test system. The results show that the fuzzy logic based coordination is able to keep the voltage within its allowable limits.

Keywords**—**Coordinated control, Distributed generation, Fuzzy logic, Voltage control.

I. INTRODUCTION

DISTRIBUTION networks in different parts of the world have gone through significant growth and improvement with the utilization of distributed generation (DGs). This is line with the policies of government of countries towards the use of renewable energy resources technology. Previously, the distribution system has been working on a unidirectional power flow but with the connection of DGs, the system has to accept bidirectional power flows which resulted in several technical issues such as voltage levels and power flow, protection issues, equipment thermal ratings and fault current levels [1]. One of the major concerns in the integration of DGs in the distribution systems is the voltage rise issue. This further requires the DNOs to find solutions to the overvoltage problems in ensuring that the customers receive the voltage within its specified limits. Two main voltage control methods in a distribution system with DGs which have been identified are categorized as coordinated or centralized control while the other one is categorized as semi-coordinated and decentralized control. The coordinated control determines their control actions based on the information from the whole network, hence requiring data transfer and communications between the network nodes. On the other hand, the decentralized control performs its actions locally with limited number of communications. Several studies in coordinated voltage control involves the development of centralized Distribution Management System (DMS) control as well as coordination of the distribution system components such as on load tap changer OLTCs and switched capacitors. As in the case for decentralized control, several methods of control particularly at the generator itself or involving the components in the system includes the power factor control (PFC), OLTC control, active power generation curtailment, and also reactive power compensation. Recently, more efforts in integrating the use of intelligent techniques in automating the control have been developed by researchers worldwide. Intelligent methods such as fuzzy logic control (FLC), artificial neural network (ANN), genetic algorithms (GA), Tabu Search algorithm, multi agent system, evolutionary programming (EP) and swarm intelligence, are examples of the methods used in providing the distribution system with a more efficient, reliable and optimized controlled environment [2]. In this work, the fuzzy inference system (FIS) which is a part of fuzzy logic control system has been chosen to coordinate the three control methods identified, power factor control, on load tap changer and generation curtailment methods. Some work which is related to the use of fuzzy logic for voltage control reviewed includes the work done in a residential area in Saudi Arabia which utilizes fuzzy logic to regulate the setting of the on load tap changer [3]. In [4], a fuzzy power factor controller for voltage regulation with multiple synchronous generators has been proposed. In the proposed scheme, the participation factors of the generators takes into account the sensitivity analysis of the individual generators. A modified fuzzy logic control scheme for managing the interaction of the in-series OLTCs in the distribution system is presented in [5]. The scheme proves to help solve the interaction problem as well as avoiding the unnecessary tap operations. A fuzzy logic power factor controller designed using the graphical user interface for a simple 2 bus system is proposed in [6]. The work focused on controlling the power factor operation in managing the voltage fluctuation issue and considers the allowable range of the voltage as input or constraint to the system developed.

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II. VOLTAGE RISE EFFECT DUE TO THE CONNECTION OF DGS

Voltage level is particularly influenced by various factors such as; line resistance R, the line reactance X, the DG power output (P_{DG}, Q_{DG}), the reactive power compensator (Q_C), the local load (P_L, Q_L), and the voltage at busbar i (V_i). Fig. 1 shows the simplified circuit for modelling the relationship between DG penetration and voltage control.

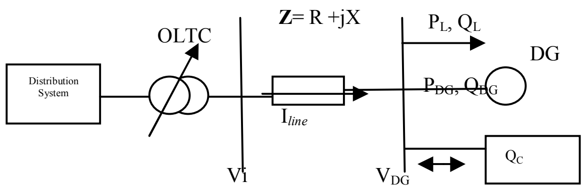

Fig. 1 A simple system connected with DG to model voltage rise

The value of voltage at the busbar connected to the DG can be approximately calculated using the equation:

$$V_{DG} \cong V_i + I_{line} \cos\theta(R) + I_{line} \sin\theta(X) \quad (1)$$
$$\cong V_i + (P_{DG} - P_L)R + (\pm Q_{DG} - Q_L \pm Q_C)X \quad (2)$$

This equation can be used to qualitatively analyze the relationship between voltage at the busbar connected to the DG and the amount of generation that can be connected to the network, as well as the impact of alternative control actions. Therefore, network voltages can be managed in planning timescales by altering R and X or in operational timescales by controlling P and Q. The three worst case operating scenarios which are always considered are known as [7]:

1. no generation and maximum system demand
2. maximum generation and maximum system demand
3. maximum generation and minimum system demand

When the demand for power is low, as in the case in weak rural distribution area, the local generation is all exported back to the primary substation, hence creating a more severe voltage rise issue. This resulted in an unstable system and losses thus requiring efficient, smart and reliable control system to help manage the issue of voltage rise.

III. Fuzzy Logic Control

Fuzzy Logic Control (FLC) uses the principles of fuzzy logic-based decision making to arrive at the control actions. In essence, some measurements (e.g. output measurements) from the system to be controlled are matched with a knowledge base of control for a particular system. By selecting a suitable input-output linguistic variables utilizing rule base, a wide range of desirable control outcomes is able to be realized. A fuzzy rule is generally a linguistic relation of the form

$$\text{IF } A_i \text{ THEN IF } B_i \text{ THEN } C_i \quad (3)$$

where A_i and B_i are fuzzy quantities representing process measurements and C_i is a fuzzy quantity representing the control signal or output. Fuzzy logic controllers consist of a set of linguistic control rules based on fuzzy implications and the rules of inference. A fuzzy knowledge base (offline) must first be developed before following these steps in developing a fuzzy logic control [8]:

1. Develop a set of linguistic control rules (protocols) that contain fuzzy variables as conditions (process outputs) and actions (control inputs to the process).
2. Obtain a set of membership functions for process output variables and control input variables.
3. Use the ‘fuzzy AND’ operation and the fuzzy implication operation on each rule in Step 1. Obtain the multivariable rule base for that rule as in Step 2.
4. Combine the relations using the fuzzy connectives ‘fuzzy OR’ or ‘to obtain the overall fuzzy rule base relationship.

To obtain a single crisp solution for the output variable, a fuzzy system aggregates all output fuzzy sets into a single output fuzzy set, and then defuzzifies the resulting fuzzy set into a single number. This process is known as fuzzy inference and is one of the most famous applications of fuzzy logic and fuzzy sets theory [9]. Fuzzy inference can be defined as a process of mapping from a given input and an output, using the theory of fuzzy sets. The fuzzy inference process includes four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs and defuzzification. Fuzzification is the first step where the crisp inputs are taken and the degrees to which the inputs belong to each of the appropriate fuzzy sets are determined. The rules are evaluated using appropriate fuzzy operator (AND or OR) to obtain a single number that represents the result. Aggregation is the process of unification of the outputs of all the rules. The defuzzification process which utilizes the aggregated output of fuzzy set to produce a single output is the final step done in this method. Two fuzzy inference techniques are the Mamdani and Sugeno methods. The Mamdani method is widely accepted in fuzzy expert systems for its ability to capture expert knowledge in fuzzy rules. However, the Mamdani method would cause computational burden. On the other hand, the Sugeno method improves the computational efficiency of the fuzzy inference and it also works well with adaptive and optimization techniques, which makes it very suitable choice for control of a dynamic non-linear systems. It is a must to tune the fuzzy logic system which has been developed by adjusting the specific fuzzy sets and fuzzy rules to meet specified requirements desired.

IV. Development of Coordinated Fuzzy Logic Voltage Control System

Simulations are carried out on an IEEE 13 bus system using the DigSilent Power Factory Software. For the simulation work, two DGs with total generation capacities that range from 1MW to 3MW are applied to the test system. Fig. 2 shows the test system used with examples of DGs connected at two of the buses.

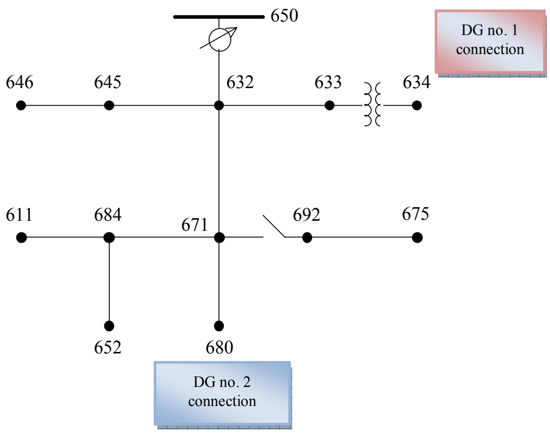

Fig. 2 The IEEE 13 bus system with two DGs connected at different load buses

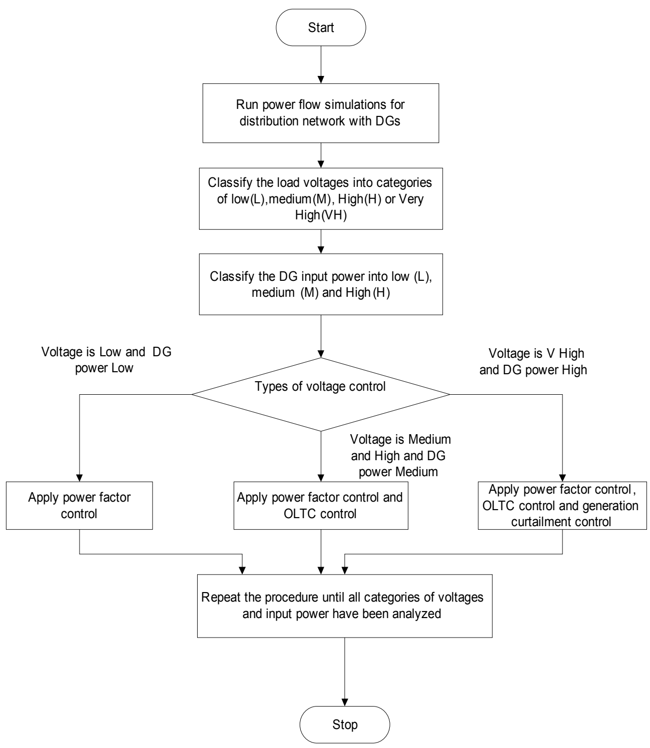

Fig. 3 Flowchart for fuzzy logic voltage control system

Fig. 3 shows the implementation of the coordinated fuzzy logic voltage control for a distribution network connected with DGs. Initially the voltage is checked at each load buses of the network. If the voltage limits are violated at any nodes, fuzzy logic actions will be taken according to the algorithm of control. It decides from which of the three modules, the power factor control, the on load tap changer and the generation curtailment control to be activated and applied when voltage is detected not to be within its permissible limits. If the chosen control option is not able to handle the voltage any longer, it is decided from the fuzzy logic controller to decide which control option is to be activated.

A. Fuzzy Logic Control Inputs Membership Functions

For this case study, the inputs to the system identified are the load voltages and DG input power. Here, the voltages which act as input to the system are classified into 4 different categories and are shown in Figs. 4 and 5 respectively.

1. Low = 0.900p.u $\le V \le$ 0.950p.u
2. Medium = 0.950p.u $\le V \le$ 1.050p.u
3. High = 1.051p.u $\le V \le$ 1.069p.u
4. Very High = 1.071p.u $\le V \le$ 1.100p.u

The second input to the system is the DG input power which is divided into three categories:

1. Low = 1MW
2. Medium = 2MW
3. High = 3MW

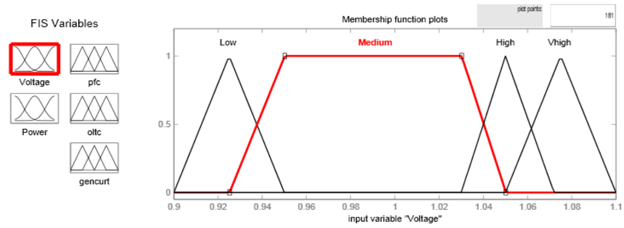

Fig. 4 Input voltage membership functions

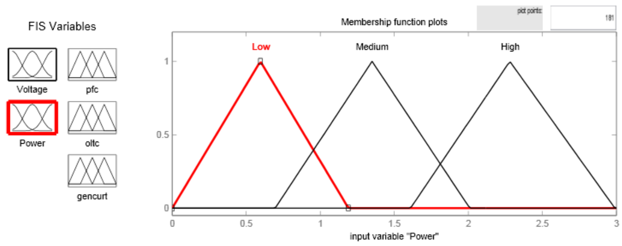

Fig. 5 DG input power membership functions

B. Fuzzy Logic Control Outputs Membership Functions

The membership functions for the outputs of the fuzzy logic control system developed are identified as the voltage control options to be activated when different ranges of input voltages and different DG input power are being fed into the system. The output control options are basically classified into 3 different categories, the PFC, the OLTC control, and the generation curtailment control. The power factor control option is firstly implemented and chosen. This is due to the fact that the generator is operating at certain power factor and has its own reactive power capability. PFC indicates the reactive power output of the generating unit maintained in proportion to the real power (MW) output such that the power factor remains constant. The reactive capability of a typical generator at a full load normally ranges between 0.85 lagging and 0.95 leading. The Distribution Network Operator in Malaysia (i.e., Tenaga Nasional Berhad) and elsewhere for example Ireland requires all generators connected to the network to operate between the power factors of 0.90 leading and lagging [10], [11]. Operating the DG in leading power factor specifically was found to mitigate the voltage rise issues

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[12], [13]. On the other hand, operating the DG at lagging power factor will increase the voltage level at the load buses and therefore is suitable for managing the lower voltage. Two operating power factor control of 0.90 and 0.95 leading are activated where the PFC at 0.95 leading is found to be suitable in the medium range of permissible voltage limits of ±5% (between 0.95 and 1.05p.u.). For voltages in the range of high and very high range, power factor of 0.90 leading is used for control. Fig. 6 depicts the output membership functions of this first control option which is categorized into 3 different generator operating options:

1. 0.85 lagging = for Low range of voltage
2. 0.95 leading = for Medium voltage
3. 0.90 leading = for High and Very High voltage

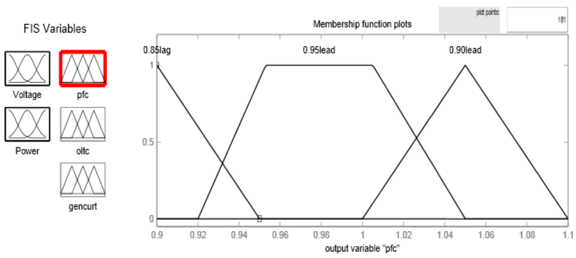

Fig. 6 Power Factor Control (PFC) membership functions

Once the limitation of the power factor control or reactive power capability has been reached, the OLTC control option is to be chosen to further help maintain the voltages within its permissible limits. The typical values of the lower limit of the deadband of the OLTC range from 0.85p.u. to 0.90p.u., whereas those of the upper limit usually range from 1.10p.u. to 1.15p.u [14]. Several works which have been carried out in different countries and environment have found that setting the OLTC set point in the range of 1.015p.u. to approximately 1.033p.u was found to be effective in managing voltage fluctuations and in limiting network losses in the study [15], [16]. In the simulation work performed, two different settings of OLTC of Vmax = 1.05p.u. and Vmax = 1.02p.u. are used where the latter was found to be more effective in managing higher levels of voltage than the setting of 1.05p.u. in managing the voltage rise in the system. Therefore, in the implementation, this second control option in priority shown in Fig. 6 is categorized into two different options:

1. 1.02p.u = for Very High range voltage
2. 1.05p.u = for Medium and High range voltage

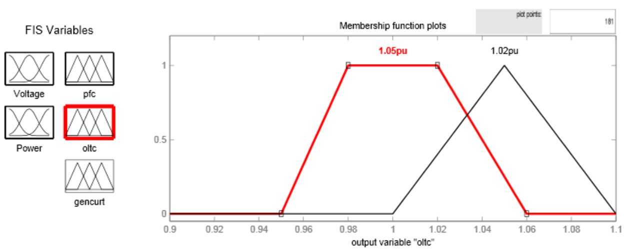

Fig.7 On Load Tap Changer (OLTC) membership functions

The lowest priority or the least preferred option of control is the curtailment control since there are various factors that need to be taken into consideration .This method is most of the time implemented to tackle voltage rise as a last resort when the generators have exhausted their capability of voltage control given there are limits to the amount of reactive power that can be absorbed or injected and curtailment is the only way to stay within statutory voltage limits [17]. Wind energy curtailment is the most frequent energy curtailed involving DGs. Several countries which practice this wind energy curtailment include the United States as well as Canada, Germany, New Zealand, Ireland, and Spain [18]. According to the work done in [15] that used a simple seven-bus system with 3 MW of DG, it is suggested that 41% of the active power must be curtailed to manage voltage rise. However, the reasonability of the percentage of curtailment must also depend on the duration of the curtailment. In this third fuzzy control shown in Fig. 8, the membership functions are categorized into two different options:

1. 0% curtailment = for low, medium and high range voltage
2. 40% curtailment = for Very High range of voltage

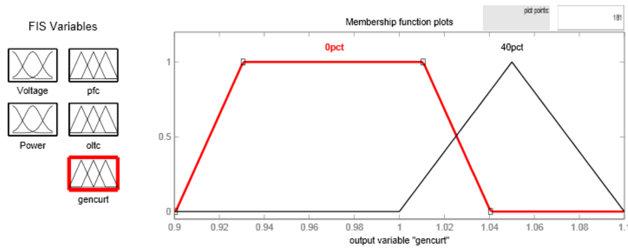

Fig. 8 Generation Curtailment control membership functions

The operating settings of the control methods coordinated in this study are based on the simulation work done previously in [19] together with review done on other distribution network voltage control experience.

C. Fuzzy Logic Control Rules

The fuzzy control system is developed using two inputs and three outputs with the outputs further detailed into different operating options. Some of the examples of the generated rules for the fuzzy logic control system are as follows with Fig. 9 illustrating the control rules captured from the program developed.

I. If voltage is low and power is low, then pfc 0.85 lag
II. If voltage is medium and power is high, then pfc 0.95lead
III. If voltage is high and power is medium, then pfc 0.90 lead, OLTC 1.02 p.u, gencurt 0%
IV. If voltage is very high and power is very high, then pfc 0.90 lead, OLTC 1.02 p.u and gencurt 40%.

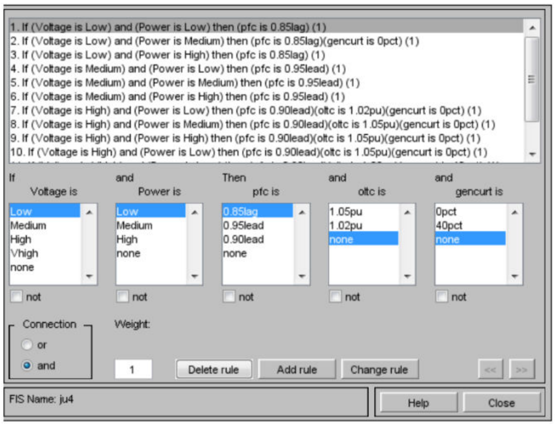

Fig. 9 Fuzzy Logic Control Rules

V. Discussion

The objective of the implementation of the fuzzy logic coordinated control is to control the voltage at the load buses within its permissible limits. Fig. 10 shows the surface viewer of control output of the fuzzy logic system.

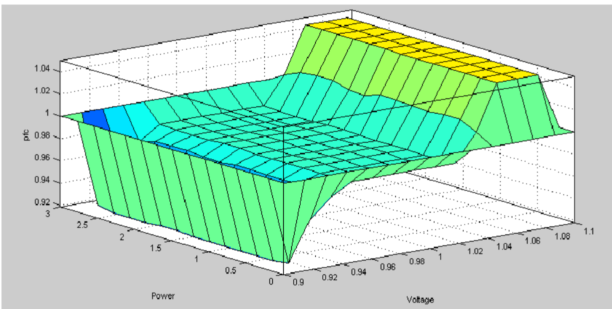

Fig. 10 Surface viewer of the fuzzy logic control output

It can be seen that for different range of inputs voltage and DG input power given, the 3-dimensional output graph shows that the output are still able to be kept within its allowable limits of not more than 1.05p.u. Fig. 11 shows the voltage profile at the load buses with and without the fuzzy logic coordination control. Without using the coordinated control, the voltages at the load buses are mostly outside the allowable maximum limit of 1.05p.u. By utilizing the fuzzy logic coordinated control, the desired output voltage range of less than 1.05p.u are still managed to be achieved.

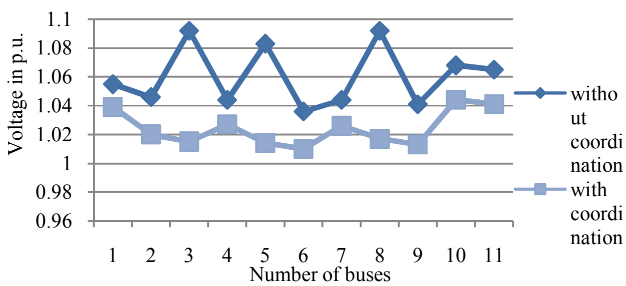

Fig. 11 Voltage profile with and without fuzzy logic coordinated control

VI. Conclusion

A coordinated voltage control methods using fuzzy logic which combines three control methods of power factor control, on load tap changer control and generation curtailment control has been developed and presented. From the results obtained, it is shown that the three control methods have been able to be coordinated and also able to control the voltage at the load buses within its allowable range of 0.95p.u to 1.05p.u. The work done here is different and new on the basis that it is coordinating three different voltage control methods using fuzzy logic, rather than using fuzzy logic system to control voltage by just using one voltage control method as done in other work reviewed. Future work will focus on finding the optimal settings of the control methods utilizing other intelligent techniques.

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