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Research paper

Voltage Stability Improvement in Power System under Different Loadings using Fuzzy Logic Technique

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Abstract

This paper presents a method for voltage stability improvement in power system under different loadings using fuzzy logic technique. Voltage stability assessment in present day plays a major role in planning and operation of power system. Therefore, it has become a challenging issue in maintaining a stable power system. To achieve this, a fuzzy-based model is developed for determining the amount of reactive power to be injected. The effectiveness of this approach will be examined using IEEE 57-bus test system. The test system is used to determine minimum voltage magnitude and fast voltage stability index, FVSI through load flow analysis. These data will be assigned as the inputs to the designed Fuzzy Inference System (FIS) for determining the injected percentage of reactive power. Experiment has validated the ability of the proposed technique and the improvement in terms of voltage magnitude was analyzed. The results have justified the effectiveness of the proposed technique in improving voltage stability of power system.

Keywords: *Fuzzy Inference System; FVSI; voltage stability*

1. Introduction

The power systems nowadays are growing day-by-day worldwide. As energy demands are increasing rapidly, the generation and power transmission capability is traditionally limited. Therefore, power system is expanding to accommodate the rapid load growth to maintain reliable and good quality of electrical supply by constructing large interconnected power networks that are operated under heavily loaded conditions, which are often close to their stability limits. Voltage instability limits are becoming more critical in the context of a secure power system operation due to the increasing energy demands. Since power systems are operated under heavily stressed condition, the ability to maintain power system stability is now one of the challenging tasks faced by the utilities [1].

Voltage stability takes place when power system is capable of maintaining steady voltages at all buses in the system when being subjected to a disturbance [2] - [4]. In this case, the operating condition that is used is variations of load demands in terms of changing real and reactive power at certain load buses. A power system that experiences a given disturbance will go through voltage collapse if post disturbance equilibrium voltages are not in the acceptable limits [5]. Voltage collapse is a process that directly leads to loss of voltages in a significant part of power system which will result in partial or total blackout [6]. Voltage security then means the ability of the system which is not only to operate stably but also to remain stable whenever there are changes occurred in the system [7] – [8]. In recent years, there are increasing number of power system blackouts in many countries [9]. This is stated to be a major concern for all electrical engineers. The problem happened due to voltage collapse that occurred in most of the power systems. The main factor influencing the voltage instability is when the system fails to meet the demand for reactive power [10]. The reason behind this lack is due to generator's reactive power limits and reactive power requirements in transmission line. Hence, analyzing system stability and monitoring reactive power sources for each load bus would help to improve voltage stability on overall.

Article [11] proposed an algorithm for the assessment of voltage stability by using Artificial Neural Network (ANN). In this method, fast voltage stability index (FVSI) is used to identify the voltage stability of power system. This method is effective as it can analyze any unknown load patterns. However, the training process of ANN takes long time in order to achieve the required data. Next, a secondary voltage control system based on fuzzy logic was proposed in [12]. In the research, modal analysis was used to identify a coherent group of buses to be monitored. The fuzzy system was employed to explore the reactive power resources and enhancing the voltage security of the power system. Based from the experiment on IEEE 118-bus test system, the proposed technique was proven to be effective for secondary voltage control strategy. Another research that applied fuzzy for stability enhancement in power system is article [13]. In the research, a power system stabilizer was designed based on conventional fuzzy PID and type-1 fuzzy controller considering multi-machine system. The study has revealed that adaptive fuzzy sliding mode controllers were better than other fuzzy models under various operating scenarios. Later, article [14] proposed fuzzy logic-based droop control of simultaneous voltage and frequency regulation in an AC microgrid. The research applied fuzzy technique for proportional integral (PI) controller in 11-bus test microgrid system. It highlights the merit of the proposed fuzzy system as the designed controller exhibits high performance and desirable response under different scenarios of load change. In [15], an adaptive PI controller was designed for voltage stability control of electric springs. The design process incorporates advanced Particle Swarm Optimization (PSO) and fuzzy control for an improved accuracy. The study has revealed that the pro-

posed adaptive PI control has better voltage regulation than the traditional one, plus that the adverse effect of the load variation was solved by the method.
This paper presents a method for voltage stability improvement in power system under different loadings using fuzzy logic technique. The problem which is not highlighted by previous researches is whether the existing methods can be used at different loadings imposed to the system. Thus, in this study the main objective is to consistently improve the voltage stability of power system under various loadings. By implementing the proposed method, the injected percentage (in terms of reactive power) at the specific bus can be determined accurately. This paper is organized as follows: (1) the basics of fuzzy logic (2) the development of algorithm for the proposed FIS (3) analysis of results concerning voltage stability improvement and (4) conclusion of this study.

2. Methodology

In this section, the systematic steps of the whole process that consists of theory on fuzzy logic and voltage improvement algorithm are explained.

2.1 Basics of Fuzzy Logic

Fuzzy logic starts with the concept of fuzzy sets where it is a set without crisp that contains elements with partial degree of membership that lies in between 0 to 1. In fuzzy logic, a FIS is designed to use fuzzy set theory to map the inputs to an output using fuzzy decision rule or *if-then rule*. Therefore, fuzzy rules use linguistic statements that provide a basis where decisions can be made regarding the classification of inputs. The inputs and output that are obtained will be plotted graphically depending on the type of membership functions chosen such as triangular, trapezoidal, and Gaussian membership function. Membership function is used to map the input of crisp value into fuzzy logic value that will be in the range of 0 to 1 [16]. There are basically two types of FIS that can be implemented, namely the Mamdani-typed and the Sugeno-typed. The Mamdani-typed FIS gives an output in the form of fuzzy set while the Sugeno-typed gives an output of either constant or linear mathematical expression [6]. The followings are the five general steps in FIS operation:

Step 1: Fuzzification – Mapping the input value from *universe of discourse* to fuzzy value between 0 and 1. The type and number of membership functions that the input belongs to are determined and mapped graphically.
Step 2: Apply fuzzy operator – Logical operator which are AND and OR operation is used to combine more than one input to form antecedent.
Step 3: Apply implication method – Implication method can be applied after determining the rule's weight in order to obtain the results of the implication. The type of logical operator chosen might affect the shape of the resulted output after this process.
Step 4: Aggregate outputs – In this step, all output membership functions are aggregated to obtain an overall shape of membership function.
Step 5: Defuzzification – This is a process where output value of fuzzy system will be converted into crisp (actual) value.

2.2. Designing Fuzzy Inference System

A Fuzzy Inference System (FIS) is designed for decision making in obtaining the output. The steps taken to design a FIS are as follows:

Step 1: set the input and output variables
The inputs and output that will be used in the FIS are determined. In this research, there will be two inputs and one output. The inputs are FVSI and minimum voltage magnitude, V_{min} while the output is the percentage of reactive power to be injected, Q_{inj}.
Step 2: develop the membership functions
After determining inputs and output, the type of membership function is chosen. For this research, there are two combinations of membership functions which are triangular and trapezoidal. This is due to the fact that both shapes are more sensitive to the change in input and output parameters.
Step 3: construct the fuzzy decision table
Once the membership functions are determined, the fuzzy decision table will be developed based on five linguistic variables, hence there will be a total of twenty five rules.
Step 4: select the logical operator
The logical operator AND is used and Mamdani-typed FIS is chosen as the model for this study.

The proposed fuzzy system has the following fuzzy decision table as in Table 1 and membership functions as in Fig. 1.

Table 1: proposed fuzzy decision table

	FVSI				
V_{min}	***ES***	***VS***	***S***	***LS***	***US***
VL	H	H	H	VH	VH
L	M	H	H	VH	VH
M	L	M	H	H	VH
H	L	M	M	M	VH
VH	VL	VL	L	M	H

Where, the linguistic variables for inputs and output are defined as follows:

- FVSI: extremely stable (ES), very stable (VS), stable (S), less stable (LS), unstable (U).
- V_{min}: very low (VL), low (L), medium (M), high (H), very high (VH).
- Q_{inj}: very low (VL), low (L), medium (M), high (H), very high (VH).

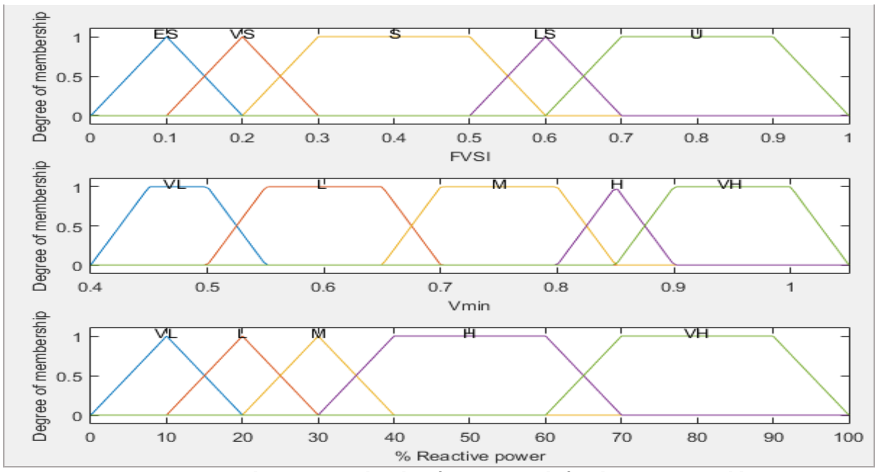

Fig. 1: Input and output membership functions with five linguistic variables

2.3. Algorithm Development

There are many compensating techniques available for improving voltage stability. Installation of FACTS devices and optimal reactive power dispatch are the preferred techniques by most researchers. For the purpose of this study, however, the scope of work has been limited to produce a general model of reactive power compensation using fuzzy logic technique. This means that the proposed fuzzy system can be incorporated with compensating devices to produce a more effective controller. Thus, in the following discussions the term 'injection' or 'injected' is used to indicate the amount of reactive power injected to the system to avoid confusion from the function of compensating devices.

A load flow analysis under various loadings is performed in order to see the effect on stability in terms of minimum voltage, V_{min} and fast voltage stability index, FVSI. Both V_{min} and FVSI are used as an indicator to determine the stability of the system. Fig. 2 illustrates the whole algorithm for the voltage stability improvement using the proposed FIS, and the step-by-step process is explained as follows:

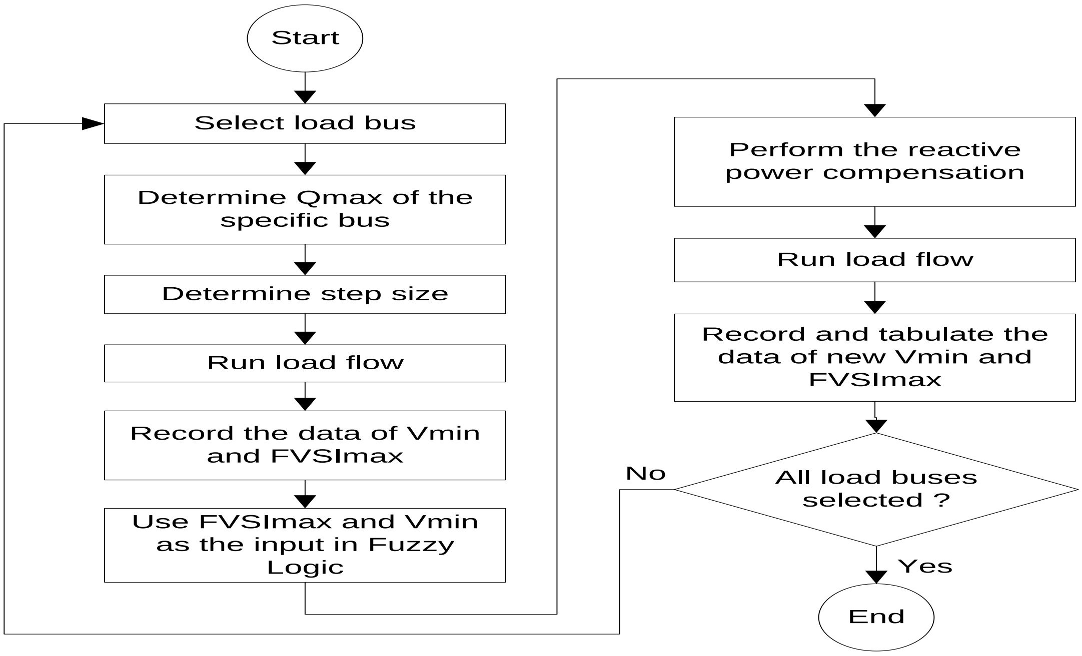

Fig. 2: Flowchart of the whole process

Step 1: A load bus from IEEE 57-bus test system is chosen. For this study, there will be two load buses chosen which are bus 38 and 57.
Step 2: After that, the maximum reactive loading, Q_{d_max} of the selected buses is determined through load flow analysis.
Step 3: The step size of each bus where the value of reactive power can be increased by 10 iterations until reaching the specific value of Q_{d_max} is determined.
Step 4: Load flow analysis is conducted at the specified condition.
Step 5: The results of V_{min} and FVSI are recorded and tabulated.
Step 6: Both V_{min} and FVSI obtained from step 5 are assigned as the inputs to the designed FIS.
Step 7: The percentage of reactive power to be injected at specific load bus, Q_{inj} is determined by running the FIS.
Step 8: The Q_{inj} is then inserted into the test system at the selected load bus.
Step 9: A post-injection load flow analysis is conducted to see the effect on voltage stability.
Step 10: The values of V_{min} at post-injection power system are obtained and tabulated.
Step 11: The whole processes from step 1 to 10 are repeated for the next buses.

3. Results and Discussion

In order to evaluate the proposed method, this section presents the result that were obtained from experiment on IEEE 57-bus test system. For this study, load buses from the test system are chosen for the determination of system stability. Two case studies that will be analysed are: (1) reactive power injection under different loadings and; (2) effects of linguistic variables on FIS's output.

3.1. Reactive Power Injection under Different Loadings

In this paper, two load buses namely bus 38 and 57 were chosen for verification. The maximum reactive loadings, Q_{d_max} for each bus were determined and the results are as follows: bus 38, Q_{d_max} = 188.28 Mvar; bus 57, Q_{d_max} = 31.05 Mvar. The rationale of choosing the two buses is due to their sensitivity on FVSI index when subjected to reactive loadings.

The minimum voltage $V_{\min}$ and percentage of reactive power to be injected, Q_{inj} were determined at every loading (i.e. from zero until Q_{d_max}) by running load flow and the developed FIS. Table 2 and Table 3 tabulate the results at pre- and post-injection for both buses. The results from both tables are illustrated in graphical forms as follows: Fig. 3 and Fig. 4 for bus 38; Fig. 5 and Fig. 6 for bus 57. It is important to note that the injection was done at the selected bus, i.e. if the loading is performed at bus 38, then the reactive power is injected at that bus.

Based on Fig. 3 and Fig. 5, the minimum voltage magnitude $V_{\min}$ was improved steadily at all loadings after injection. This holds true for both buses. The proposed fuzzy system managed to maintain the voltage above 0.90 p.u. At the worst loading of $Q_{d\_\max}$, which is the most heavily loaded condition, the fuzzy system improved the voltage to an acceptable level as follows: from 0.474 p.u. to 0.963 p.u. at bus 38 and from 0.595 p.u. to 0.927 p.u. at bus 57.

The comparison between the amount of injected reactive power and voltage increment can be seen in Fig. 4 and Fig. 6. The injected percentage at bus 38 increases gradually with the voltage increment as can be seen in Fig. 4. As the loading reaches 146.44 MVar, however, the injected percentage increases significantly from 50 percent to 80 percent. Until the loading reaches its maximum value of 188.28 MVar, it drops back to 50 percent. The percentage of voltage increment increases for the whole loadings. The highest increment is at the maximum loading where the voltage has been increased to 100 percent of its original value. The same goes for bus 57 as in Fig. 6. Between 0.00 MVar and 24.15 MVar of loading, the injected percentage increases slowly until 27.6 MVar. At this point, the injected percentage becomes 80 percent and maintains until maximum loading. With such trend of injection, the voltage increment increases consistently from the initial loading until maximum.

On overall, it can be said that the voltage increment increases with the injected percentage. This analysis justifies the effectiveness of the proposed fuzzy system, that is, providing injection with right amount of reactive power.

Table 2: Pre- and post-injection at bus 38

Q_d (MVar)	Q_{inj} (%)	$V_{\min}$ (p.u.)	
		Pre	Post
0	31.3	0.816	0.975
20.92	37.3	0.795	0.97
41.84	41.2	0.771	0.97
62.76	45.5	0.746	0.968
83.68	49.4	0.723	0.968
104.6	50	0.693	0.967
125.52	50	0.66	0.966
146.44	80	0.616	0.965
167.36	80	0.555	0.964
188.28	50	0.474	0.963

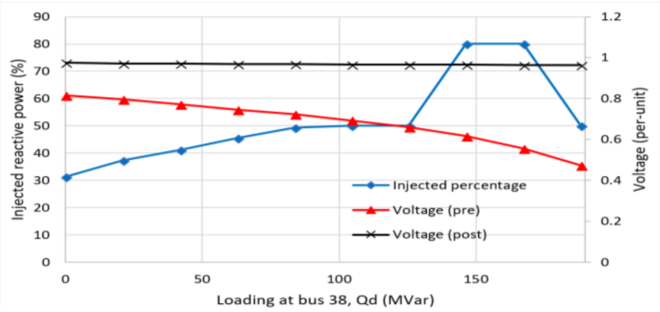

Fig. 3: Voltage at pre- and post-injection – loading at bus 38

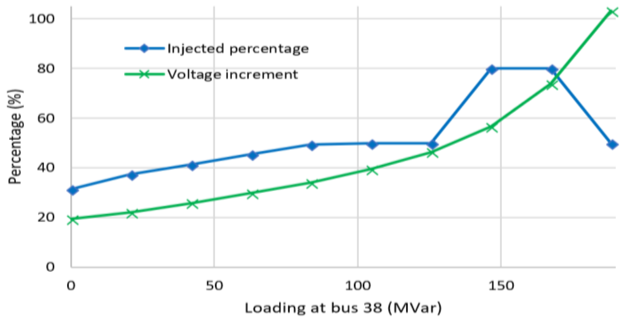

Fig. 4: Voltage increment after injection – loading at bus 38

Table 3: Pre- and post-injection at bus 57

Q_d (MVar)	Q_{inj} (%)	V_{min} (p.u.)	
		Pre	Post
0	30.6	0.817	0.927
3.45	32.7	0.813	0.927
6.9	34.5	0.81	0.927
10.35	48.5	0.807	0.926
13.8	50	0.8	0.926
17.25	50	0.776	0.928
20.7	50	0.744	0.928
24.15	55.2	0.708	0.927
27.6	80	0.658	0.927
31.05	80	0.595	0.927

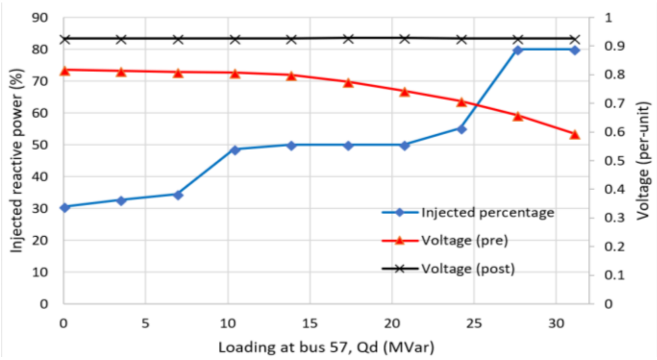

Fig. 5: Voltage at pre- and post-injection – loading at bus 57

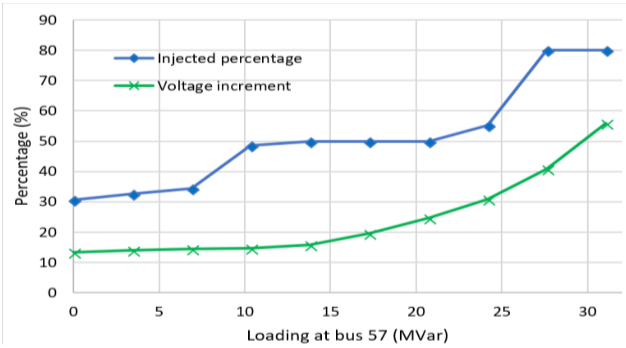

Fig. 6: Voltage increment after injection – loading at bus 57

3.2. Effects of Linguistic Variables on Fuzzy Logic Decision

For this case, the study is analyzed by comparing two fuzzy models developed in this study, namely model A and B. Model A consists of five linguistic variables, which means a total of twenty five decision rules as shown in the methodology section, while model B has three linguistic variables with a total of nine rules. The purpose of this study is to see the effect of linguistic variable adjustment to the performance of fuzzy model. Both models are measured in terms of voltage magnitude at post-injection. Table 4 tabulates the results for the two fuzzy models, while Fig. 7 and Fig. 8 illustrates the graphs of voltage improvement and voltage increment at various loadings.

Based on Fig. 7, the two fuzzy models have improved the voltage far above the pre-injection (i.e. pre-compensation). In terms of consistency, model A offers a steadier improvement than model B. This can be seen in Table 4 where the improved voltages by model A are all above the nominal value of 0.95 p.u. Model B, however, did not improve the voltage as that of model A. At most of the loadings, the voltages improved by model B are below the nominal value. Perhaps a smaller number of linguistic variables used in making the decision has caused the fuzzy model to produce inaccurate output.

Table 4: Voltage at post-injection based on two fuzzy models

Q_d (MVar)	Pre V_{min} (p.u.)	Post V_{min} (p.u.)		Q_{inj} (%)	
		Model A	Model B	Model A	Model B
0	0.816	0.975	0.895	31.3	20.0
20.92	0.795	0.97	0.899	37.3	25.2
41.84	0.771	0.97	0.921	41.2	36.2
62.76	0.746	0.968	0.920	45.5	40.0
83.68	0.723	0.968	0.906	49.4	40.0
104.6	0.693	0.967	0.892	50	40.0
125.52	0.66	0.966	0.958	50	71.3
146.44	0.616	0.965	0.958	80	75.0
167.36	0.555	0.964	0.952	80	75.0
188.28	0.474	0.963	0.886	50	55.0

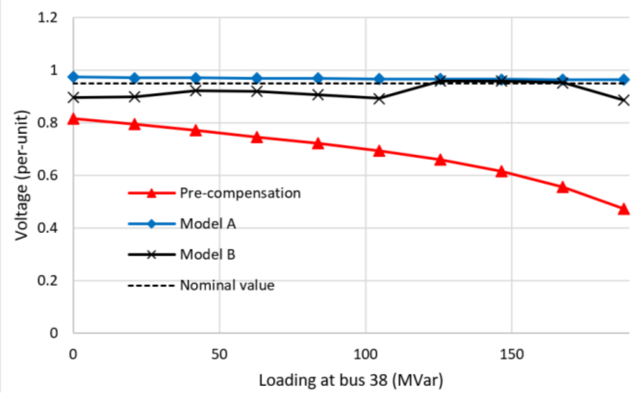

Fig. 7: Voltage improvement by two fuzzy models – loading at bus 38

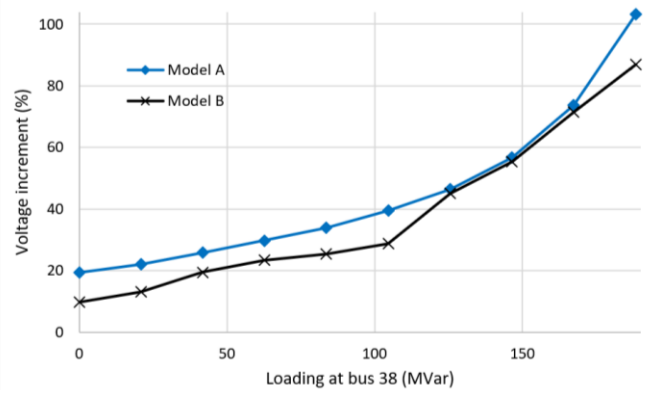

Fig. 8: Voltage increment after injection by two fuzzy models – loading at bus 38

In terms of the voltage increment produced by both fuzzy models, it can be observed in Fig. 8 that model A provides larger increment than model B. This is logical since the percentage of injected reactive power (Q_{inj}) produced by model A is a bit higher than model B. Based on Table 4, model A has higher injection percentage than model B at the following loadings: from 0 to 104.6 MVar and from 146.44 to 167.36 MVar. Only at two loadings of 125.52 MVar and 188.28 MVar does model B has higher injection percentage than model A. At the last loading of 188.28 MVar, the voltage improved by model B is far below the model A although its injection percentage is higher than another.

On overall, it can be said that model A with five linguistic variables offers a better voltage improvement than model B with just three linguistic variables. Thus, it is justified that deciding good linguistic variables is significant in fuzzy model design. Improper selection on the linguistic variables can cause inaccurate decision made by the fuzzy model.

4. Conclusion

In conclusion, this paper has presented a method for voltage stability improvement in power system under different loadings using fuzzy logic technique. The intelligence of the fuzzy model to give accurate decisions on the injection percentage was demonstrated in this paper. It was justified that the proposed fuzzy model was able to improve the voltage magnitude at satisfactory level: above 0.95 p.u. for bus 38 and above 0.90 p.u. for bus 57. The accuracy of the proposed fuzzy model is independent of the system loadings: it can give consistent improvement on the voltage profile regardless of the loadings imposed to the system. This can be considered as a proof of the method's robustness over other existing techniques. For future recommendation it is aspired that the developed fuzzy system can be applied with other compensating devices (i.e. FACTS devices) to give a realistic compensation. This means that a proper modelling of the compensating devices with the incorporation of fuzzy system as the controller is needed.

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