Fuzzy Adaptive Droop Controlled Parallel Inverters for Microgrid Applications

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***Abstract*— Due to rising energy consumption and global climate change difficulties, distributed generation, smart grid, and renewable energy technologies are gaining traction as solutions to global problems. Conventional power systems have been prone to reliability issues, especially with the increase in the electrical power grid. In future, microgrids (MGs) will become a potential trend in power systems. The prime focus of this paper is on the parallel control of inverters which act as grid forming inverters. A comparative study and analysis was done on the droop control, fuzzy adaptive droop control of the voltage source inverters in a stand-alone MG. Droop control scheme imitates the droop characteristics of generators in a conventional grid and controls the frequency and terminal voltage of output in accordance with variation in output power. It allows for decentralized control without the need for external communication lines. These solutions allow for a "plug-and-play" interface and improve system reliability. However, these inverters have no ability to inject virtual inertia adaptively as per power variations. It's prone to slow transient response and frequency and amplitude deviations, and ineffective reactive power-sharing. A novel adaptive droop control scheme with fuzzy logic based virtual moment of injection was proposed to address the issues. In this way, when there's any deviation in frequency and voltage due to disturbances, the proposed model adaptively varies the droop coefficients to provide better transient response. The simulation results of both the control schemes were compared and an improvement in performance was observed in the adaptive mode.**

Keywords*— *Droop Control; Adaptive moment of Inertia; Parallel Inverters; Microgrid; Fuzzy Controller.

I. INTRODUCTION

The grid-forming inverters uprising is particularly interested in controlling parallel inverters for voltage and frequency regulation and enables reliable power distribution inside an autonomous grid, such as a microgrid (MG), or within a larger system. Current source inverters (CSIs) are typically employed to inject current into the grid, while voltage source inverters VSIs are required to maintain the voltage consistent in island or autonomous operation. Deriving different control strategies for efficient power sharing and reliability has been a popular area of research interest in the field of power systems and power electronics. This also develops motivation of our project to implement the control strategies and analyze their operations [1-5].

Droop control is achieved by mimicking the droop characteristic of generators in a conventional power grid and regulating the frequency and voltage of the VSI output terminal in response to output power variations. The control scheme is based on parallel-connection inverter technology. Because all distributed generations (DGs) are connected to the MG by inverters, the MG in islanded mode is the same as having numerous inverters connected in parallel [6-9]. The so-called distributed generation, which connects generation to the distribution network, is gaining popularity. DG refers to mini-scale generation that is ideally situated near demand to minimize power losses.

Many DG units distribute load power among themselves in microgrid operating in islanded mode. Droop control comes under one of the most flexible and recognized control methods for power sharing. It doesn't require any inter-communication between the inverters and hence can helps in cost saving. Both active power and reactive power injection from the inverters into the power grid can be done using droop control by regulating the voltage and frequency at the output terminal. Droop control technique has become popular because it allows for decentralized control without any dependence on outer communication. It also enhances system reliability and allows for plug and play interface. Anyway, external communication links can be used in addition with the droop control for further system performance improvement. It's prone to frequency deviations and voltage deviations and sluggish transient response [10-13]. Can cause circulation currents if there's any mismatch of impedance between the output side of the inverters and the load bus side or if there's any error in terms of measurement values of voltage/currents.

Power electronic VSIs have no ability to inject virtual inertia adaptively since they have no rotational inertia. If there's any transient disturbance in the grid or load side, then conventional droop control may not be able to handle the disturbance properly. Droop control can only handle steady state disturbances. Fuzzy Controller can be used to vary the droop coefficients adaptively by injecting the virtual inertia and thereby improving the transient response of frequency and voltage [14-17].

This work is divided into four distinct portions. The first portion is the introduction, followed by the controller implementations in the second section. In part three, simulation results and discussions are presented. Section four contains final observations on the aforesaid control approaches.

II. CONTROLLERS

A. *Droop Controller*

Droop control is a means of replicating a classic generator's drooping characteristics. The control technique is used especially when many inverters are operating in parallel without any communication among them. The concept of operation is as follows: To ensure a suitable

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allocation of active and reactive power in the system, every individual inverter self-detects its own output power at its respective terminal and then adjusts it with respect to a reference output frequency and voltage produced through droop control. This control method can be used to link MGs as well. Each distributed resource can automatically adapt its output active power and reactive power and participate in grid frequency and voltage when the grid's voltage and frequency change. Because of the inertia of the power system and the drop in frequency with increasing load, inverter parallel operations have used the droop control approach. Since RES are directly connected with the help of power electronic components, the system inertia has been ignored in the MG. Hence, using a droop control technique, the inertia of a voltage source inverter (VSI) can be imitated like a synchronous wind turbine generator (WTG) system.

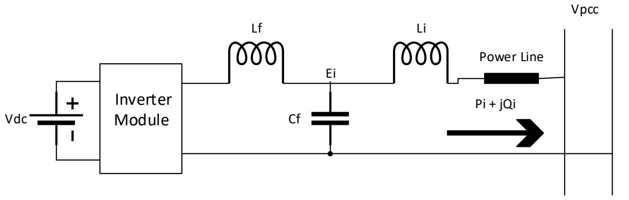

Fig. 1. Model diagram of a DG Unit.

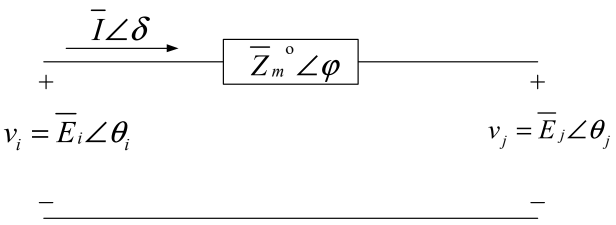

Fig. 2. Power flow between the two nodes through a line.

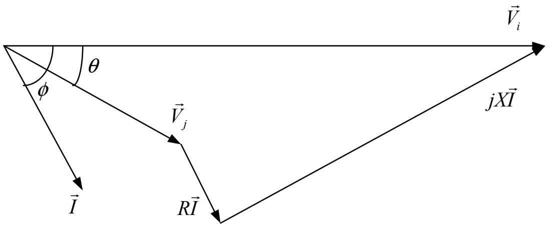

Fig. 3. Phasor diagram of the connection.

Mathematical Modelling of Droop Control

The complex power flow expressed from bus *i* to bus *j* is:
The complex power flow expressed from bus i to bus j is:

$$S = P_{ij} + jQ_{ij} \tag{1}$$

$$VI^* = V_i\left(\frac{V_i - V_j}{Z_m}\right)^* = \frac{\overline{E_i}}{\overline{Z}_m e^{-j\phi}}(\overline{E_i} - \overline{E_j}e^{j\theta}) \tag{2}$$

where, θ is the angle difference between bus *i* and bus *j*. Separating the total complex power into components of real and imaginary parts,

$$P_{ij} = \frac{\overline{E_i}^2}{\overline{Z}_m}(\cos\phi) - \frac{\overline{E_i}\,\overline{E_j}}{\overline{Z}_m}\cos(\theta+\phi) \tag{3}$$

$$Q_{ij} = \frac{\overline{E_i}^2}{\overline{Z}_m}(\sin\phi) - \frac{\overline{E_i}\,\overline{E_j}}{\overline{Z}_m}\sin(\theta+\phi) \tag{4}$$

Further writing the line impedance as $Z_m = R_m + jX_m$

$$P_{ij} = \frac{\overline{E_i}}{R^2 + X^2}[R(\overline{E_i} - \overline{E_j}\cos\theta) + X\overline{E_j}\sin\theta] \tag{5}$$

$$Q_{ij} = \frac{\overline{E_i}^2}{\overline{Z}_m}(\sin\phi) - \frac{\overline{E_i}\,\overline{E_j}}{\overline{Z}_m}\sin(\theta+\phi) \tag{6}$$

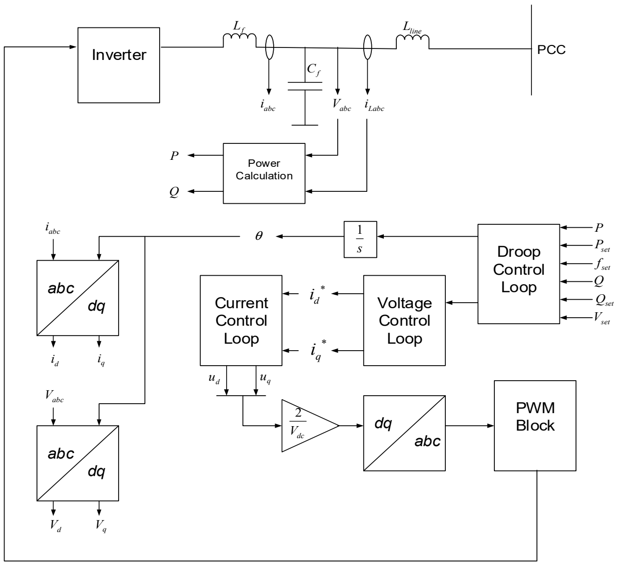

Fig. 4. Overall Block Diagram of Conventional Droop Control.

B. Fuzzy Adaptive Droop Control

Fuzzy control unlike the traditional control techniques can be used in complex and non-well defined problems whose underlying system dynamics are unknown. Fuzzy inference system involves various sub units like fuzzy logic operators(and, or etc.,), fuzzy membership functions, if-then rules which map the input values to output vales. In the past two decades, the usage of fuzzy logic controller in various power system applications has increased tremendously. Based on the previous experience of the system and human expertise, fuzzy logic can be applied to a system for controller designing. Various components of the Fuzzy system were described as follows:

- **Fuzzifier:** Used to convert the crisp logic (Boolean 0 and 1s) inputs to fuzzy logic values.
- **Fuzzy Knowledge Base**: It contains the input and output membership functions which map the input values to rule base of fuzzy system and the output variables to the controlled plant.
- **Fuzzy Rule Base**: It stores the information about various if-then rues which map the input variables to output vales which define the process operation.
- **Inference Engine**: It is the component that performs reasoning to simulate the decisions given the human operator. It's the kernel of any Fuzzy Logic Control.
- **Defuzzifier:** It is used to convert back the fuzzy values at the output side to crisp values form the fuzzy inference system.

Mathematical Modelling of Fuzzy Control

In the proposed adaptive droop control technique, the droop coefficients were modified in accordance to the plant disturbances. Therefore, any modification in frequency droop coefficients injects and adaptive moment of inertia virtually into the system and thereby enhancing the transient response of frequency. In the same way, modification of voltage droop coefficients adaptively enhances the output voltage response. The modified droop coefficients have two parts namely, fixed part and variable part. The fixed part is half the maximum droop coefficient value and the variable part varies such that the overall coefficient varies in the range of 0 to 100% of maximum value.

Conventional Synchronous generator swing equation was used for virtual inertia injection in Fuzzy Model based Droop Controller. The proposed controller takes frequency deviation into account and injects virtual inertia adaptively to give better frequency response. Also, it can improve the reactive power sharing since it took both the voltage deviation percentage ($\%v\_dv$) and rate of change of voltage (ROCOF) into account to calculate K_{qv}.

$$\omega = \omega_{ref} + K_{pw}(P_{ref} - P) \tag{7}$$

$$V = V_{ref} + K_{qv}(Q_{ref} - Q) \tag{8}$$

$$P_{ref} - P = J\omega_{ref}\frac{d\omega}{dt} + D(\omega - \omega_{ref}) \tag{9}$$

The modified droop coefficients have two parts namely, fixed part and variable part. The fixed droop values are taken as half the rated values and the remaining half will be variable as injected by the controller.

$$K_{p\omega} = K_{p\omega}^{0} + K_{p\omega}^{f} \tag{10}$$

$$K_{qv} = K_{qv}^{0} + K_{qv}^{f} \tag{11}$$

$$K_{p\omega}^{0} = \frac{K_{p\omega}}{2} = \frac{\omega_{\max} - \omega_{\min}}{2P_{ref}} = 5\times10^{-3} \tag{12}$$

$$K_{qv}^{0} = \frac{K_{qv}}{2} = \frac{V_{\max} - V_{\min}}{2Q_{ref}} = 1.25\times10^{-5} \tag{13}$$

The obtained moment of inertia relation is given by,

$J \alpha \dfrac{1}{K_{p\omega}}$ (τ and ω_{ref} are constants)

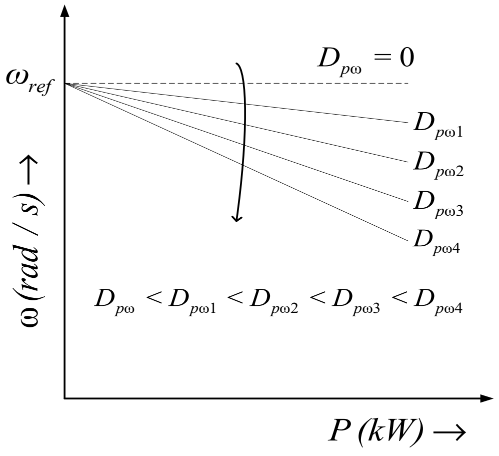

Fig. 5. P-ω droop characteristics.

From the above equations, graphs were plotted between P-ω, Q-v and moment of inertia. Since, Moment of inertia is inversely proportional to frequency Droop Coefficient, we observe that for flat line of ω_{ref}, moment of inertia should be ideally infinite and goes on decreasing with below slantier graphs. However, in the P-ω graph, frequency droop coefficient is zero ideally for flat line i.e., no change in ω_{ref} with change in power, and goes on increasing below.

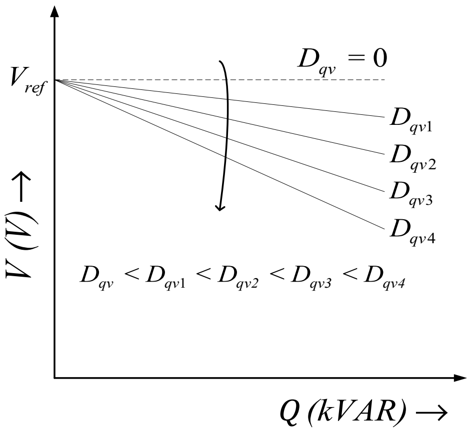

Fig. 6. Q-v droop characteristics.

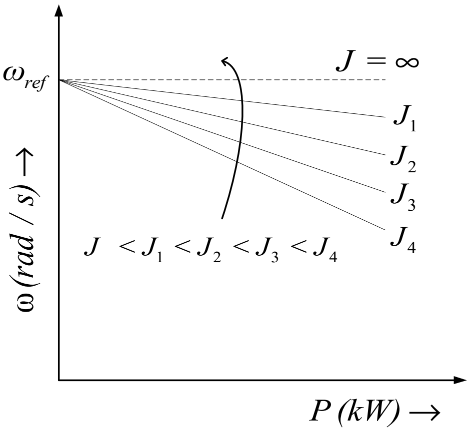

Fig. 7. Moment of inertia graph

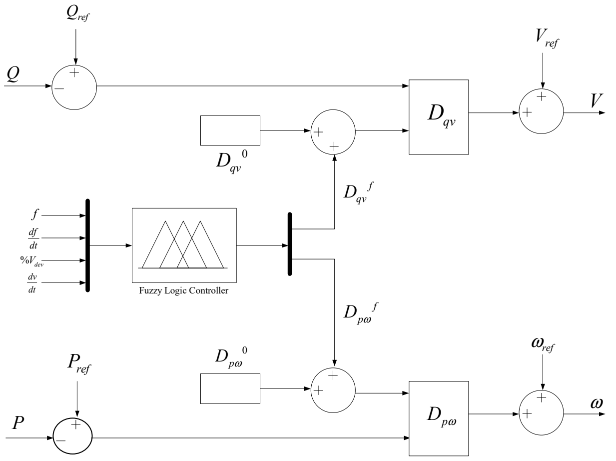

Fig. 8. Proposed Fuzzy Controller.

In this novel method, the base droop coefficients (fixed value) were added with the variable part generated by the Fuzzy logic controller and fed into the conventional droop controller which governs the power sharing of inverters. The fuzzy controller has four inputs namely, frequency, ROCOF voltage deviation percentage and rate of change of voltage and two outputs namely, K_p and K_q along with three triangular membership functions with NV (Negative Deviation), ZE (Medium Deviation) and PV (Positive Deviation).

Fuzzy Rules

Based on the previous experience of the system and deviation of voltage and frequency from nominal values, 10 fuzzy rules were formulated are shown in Table I and II, five each for frequency droop coefficient and voltage droop coefficients respectively.

Table I Fuzzy Rules to obtain frequency droop coefficient

f	$\frac{df}{dt}$	$D_{p\omega}$
PV	PV	NV
PV	NV	ZE
ZE	ZE	ZE
NV	PV	ZE
NV	NV	NV

Table II Fuzzy Rules to obtain voltage droop coefficient

$\%V_{dev}$	$\frac{dv}{dt}$	D_{qv}
PV	PV	NV
PV	NV	ZE
ZE	ZE	ZE
NV	PV	ZE
NV	NV	NV

The fuzzy rules were formulated by taking into the account the voltage and frequency characteristics with respect to disturbances. When there’s more deviation of the response from the nominal value, large inertia value will be injected and when the response is deviating towards the nominal value, lower value of inertia will be injected.

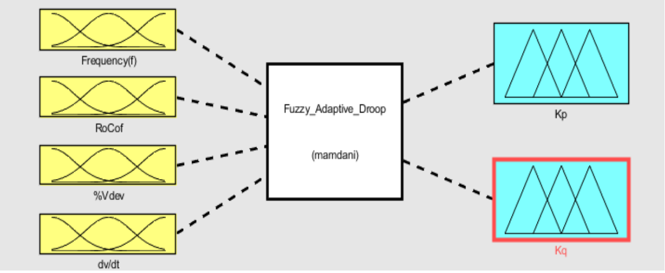

Fig. 9. Fuzzy Information System Block in Simulink.

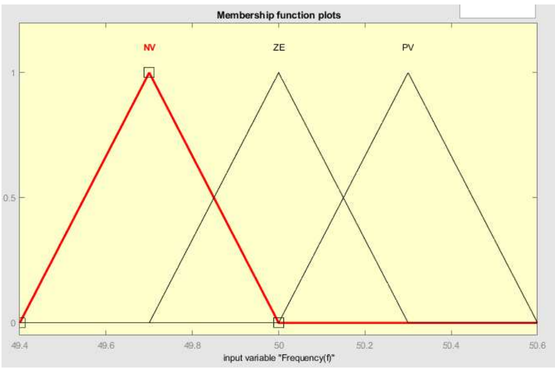

Fig. 10. Input Membership Function of Frequency

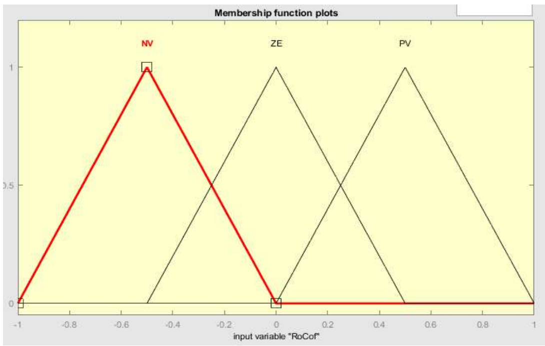

Fig. 11. Input Membership Function for Rate of Change of Frequency

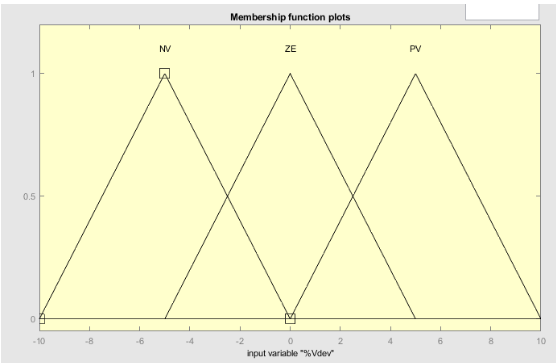

Fig. 12. Input Membership Function for Percentage of Voltage Deviation

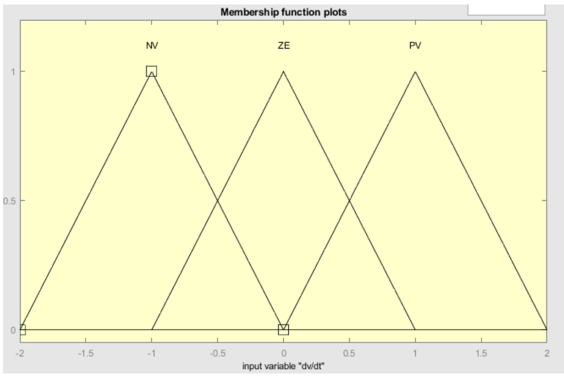

Fig. 13. Input Membership Function for Rate of Change of Voltage

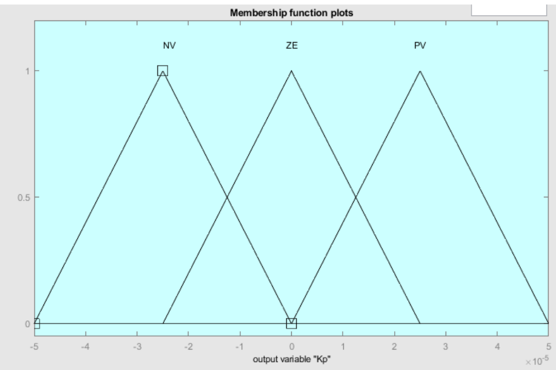

Fig. 14. Output Membership Function for Frequency Droop Coefficient.

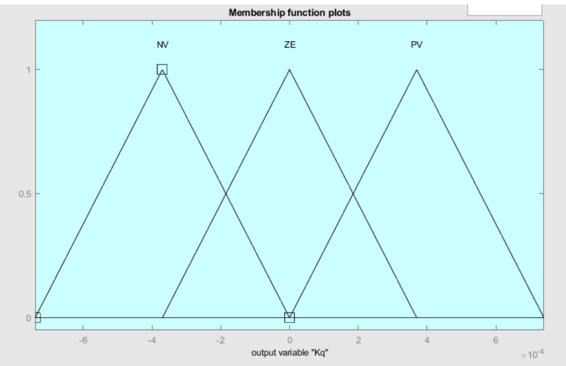

Fig. 15. Output Membership Function for Voltage Droop Coefficient

III. SIMULATION RESULTS

Simulation of both control strategies was done and several waveforms numbering from figure 16 to 26 were extracted from Simulink using a scope. The following observations were made from the waveforms. During equal load distribution using droop control, Fig. 16 shows the droop voltage, which fluctuates a bit during load disturbance from 0.2 to 0.4 seconds. Also, the droop current at the output of inverter has a value of around 2.5 A initially and with increase in load, we observe that droop current increases to 3.8A shown in Fig. 17. Fig. 18 shows the active power sharing by both the parallel inverters. Since, both the inverters have same parameters; both nearly shared the load in equal ratios.

Table II Simulation parameters

Parameter	**Value**
Load	(2kW+j1.5kVAR) + (1kW+j7.5kVAR) (for t=0.2 to 0.4 sec)
Simulation Time	0.6 sec
Filter Parameters	$L = 10mH; \quad C = 50\mu F$
Droop Coefficients	Inverter 1: $K_f = 2.5\times10^{-4}; \quad K_v = 10\times10^{-3}$ Inverter 2: $K_f = 2.5\times10^{-4}; \quad K_v = 10\times10^{-3}$
DC Voltage	850V
System Frequency	50Hz
PCC Voltage(L-L)	415V

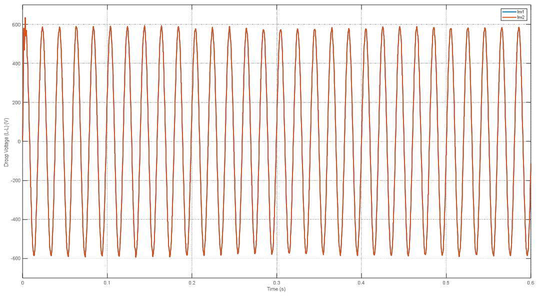

Fig. 16. Output Line to Line Voltage of Inverters.

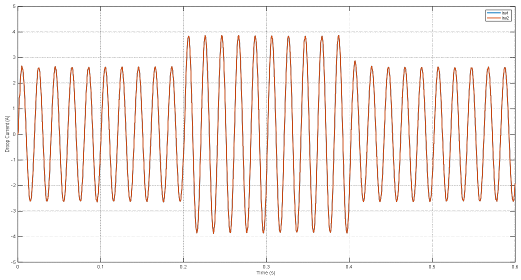

Fig. 17. Output Line Currents of Inverters

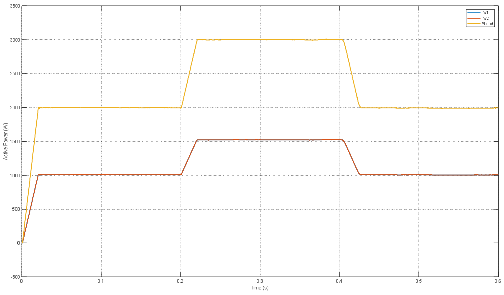

Fig. 18. Active power sharing by the two inverters

Fig. 20 shows the reactive power sharing. Although both the inverters follow each other, the reactive power is not shared as demanded by the load. In case of fuzzy control, from Fig. 21, we observe that the droop voltage fluctuation is well regulated during disturbances with minimal fluctuations. Fig. 22 shows the current sharing between the inverters using fuzzy control. The active power output of individual inverters exactly tracks the reference active power produced by the fuzzy controller and hence there's precise sharing of active power. Figs. 23 to 26 show the active and reactive power sharing by the inverters in fuzzy control, which has also improved the sharing significantly.

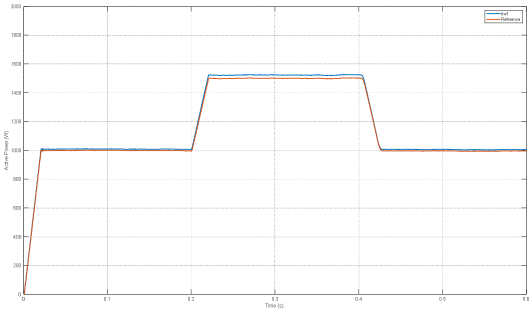

Fig. 19. Active Power Reference Tracing by individual inverter.

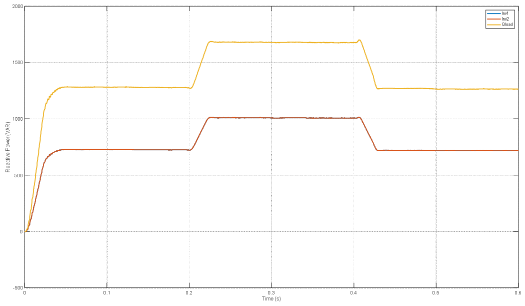

Fig. 20. Reactive Power Sharing by both the inverters

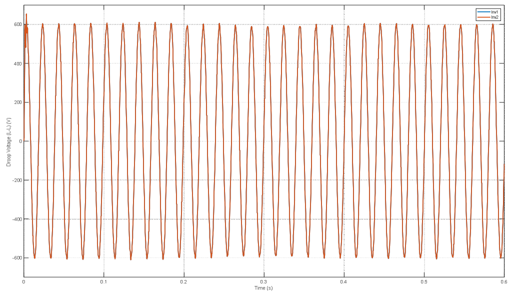

Fig. 21. Output Line to Line Voltage of Inverters

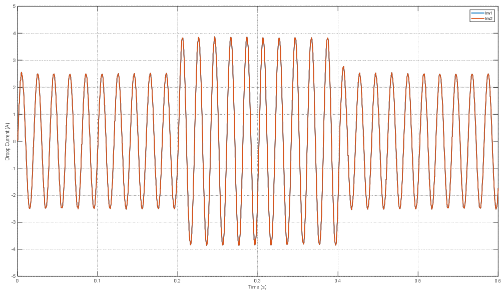

Fig. 22. Output Line Currents of Inverters

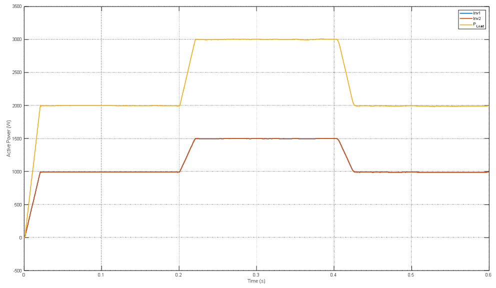

Fig. 23. Active Power Sharing by two parallel inverters

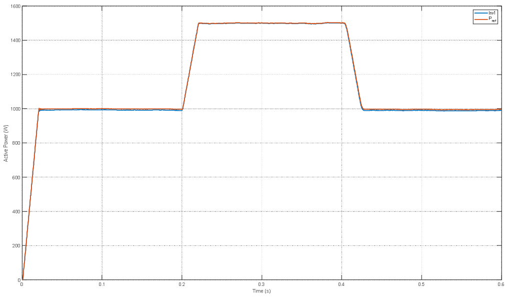

Fig. 24. Active Power Reference Tracing by an individual inverter

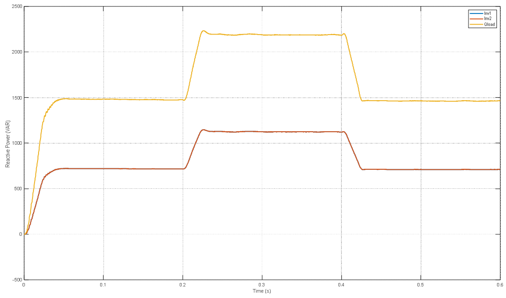

Fig. 25. Reactive Power Sharing by two parallel inverters

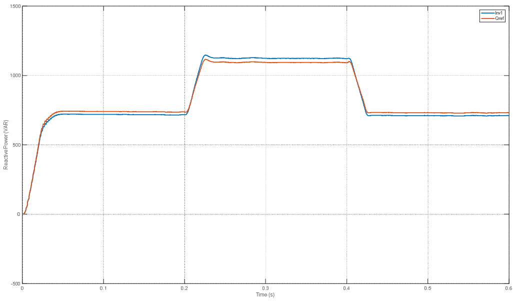

Fig. 26. Reactive Power Reference Tracing by an individual inverter

IV. CONCLUSION

Different control strategies of parallel control of inverters in stand-alone mode of operation were simulated and analyzed. Droop control of parallel inverters is simple and easy to implement, communication free and mimics the droop characteristics of conventional synchronous generators. Modified Droop Control has good active power sharing capabilities. However, it's prone to voltage amplitude and output frequency deviations and sluggish transient response, inefficient reactive power sharing especially when there's a mismatch between line impedances between the inverters and load and during unequal power distribution. Because of these limitations and issues with conventional droop control, a novel concept of Fuzzy logic based adaptive virtual inertia control was proposed as an extension to droop control in the paper. The proposed technique enhanced reactive power sharing and voltage response in real time disturbances and hence maintains a good and reliable grid integration to meet the load demands. Compared to conventional droop control, fuzzy adaptive droop control has effective active powers and reactive power sharing along with better transient performance. In the case of unequal sharing of loads, both the inverters operating in parallel, share the load in their respective ratings and maintain synchronization.

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