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# Reduced Negative Effect Delay ForMulti-Machine Power System Using Fuzzy Logic Controlled Bridge Type Fault Current Limiter

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***Abstract*—Thispaper proposes a fuzzy logic controlled bridge type fault current limiter (FCL) to enhance the transient stability of multi-machine power systems. The transient stability performance of the fuzzy logic controlled bridge type FCL is compared with that of another static nonlinear controlled bridge type FCL. The total kinetic energy (TKE) of the generators in the system is used to determine the transient stability enhancement index. Also, the critical clearing time has been presented as a stability limit. Instead of conventional reclosing, the optimal reclosing of circuit breakers is considered. Simulations are performed by using the Matlab/Simulink software. Simulation results of both permanent and temporary faults at different points of the IEEE 30-bus power system indicate that the fuzzy logic controlled bridge type FCL can enhance the transient stability of the system well. Also, the performance of the proposed fuzzy logic controller is better than that of the static nonlinear controller.**

***Index Terms*—Bridgetype FCL(Fault Current Limiter), fuzzy logic controller (FLC), nonlinear controller, optimal reclosing, power system transient stability.**

## I. INTRODUCTION

TRANSIENT stability is the ability of a power system to re-gain its stability in case of sudden and severe faults in the system [1]. The time interest for the transient stability is 0 s to 10 s [1]. In case of faults on the transmission line, the circuit breakers open to protect the healthy section and then reclose again after the fault arc de-ionization in order to maintain continuity of power [1]. In most of the cases, circuit breakers are reclosed with high speed after a fixed time interval.

There are several methods and auxiliary devices for enhancing the transient stability of power systems. Among the auxiliary stability enhancing methods, the braking resistor [2], [3], flexible AC transmission systems (FACTS) devices [4], [5], superconducting fault current limiter (SFCL) [6]–[10], static VAR compensator (SVC) [4], [5], [11], superconducting magnetic energy storage (SMES) [12], [13], etc., are popular and getting more applications day by day.

In power systems, fault current limiters are used to decrease the magnitude of fault current [14]–[21], and thus improve the transient stability of the system. Fault current limiters introduce fixed impedances in the event of faults and thus reduce the effect of high fault current level in the system [14]–[2 1].

The bridge type fault current limiter (BFCL) is currently a very much popular auxiliary stability improving device to the power engineers and researchers throughout the world [14], [15], [22]. Day by day, it is getting more attraction for its simple structure, low cost and feasible implementation characteristics. But, up to now, there is no detailed analysis of its proper and rigid control structure. Although there is an interesting work on the control structure of bridge type fault current limiter [14], but the proposed control system lacks in viable implementation of generator responses as any control status [14]. Moreover, it depends only on the grid current and voltage responses which can change nonlinearly any time. The line current variation during fault is compared with a predefined threshold line cur-rent value, which can vary depending upon the systems nature and fault condition.

Therefore, as the power system is nonlinear in nature, a non-linear controller for the bridge type fault current limiter will be reasonable from the view point of stability improvement of the power systems. As fuzzy logic controller is a nonlinear controller with simplicity, it can be easily implemented for power system stability improvement [2], [3], [13], [23], [24]. It is a very simple nonlinear controller based on simple "IF-THEN" logic. It resembles human decision making with its ability to work from approximate data and find precise solutions [2], [3], [13], [23], [24].

### A. *Power System Stability*

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individual characteristics.

Further, devices used to protect individual equipment may respond to variations in system variables and thereby affect the power system performance. A typical modern power system is thus a very high-order multivariable process whose dynamic performance is influenced by a wide array of devices with different response rates and characteristics. Hence, instability in a power system may occur in many different ways depending on the system topology, operating mode, and the form of the disturbance. Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or, colloquially, in step. Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system.

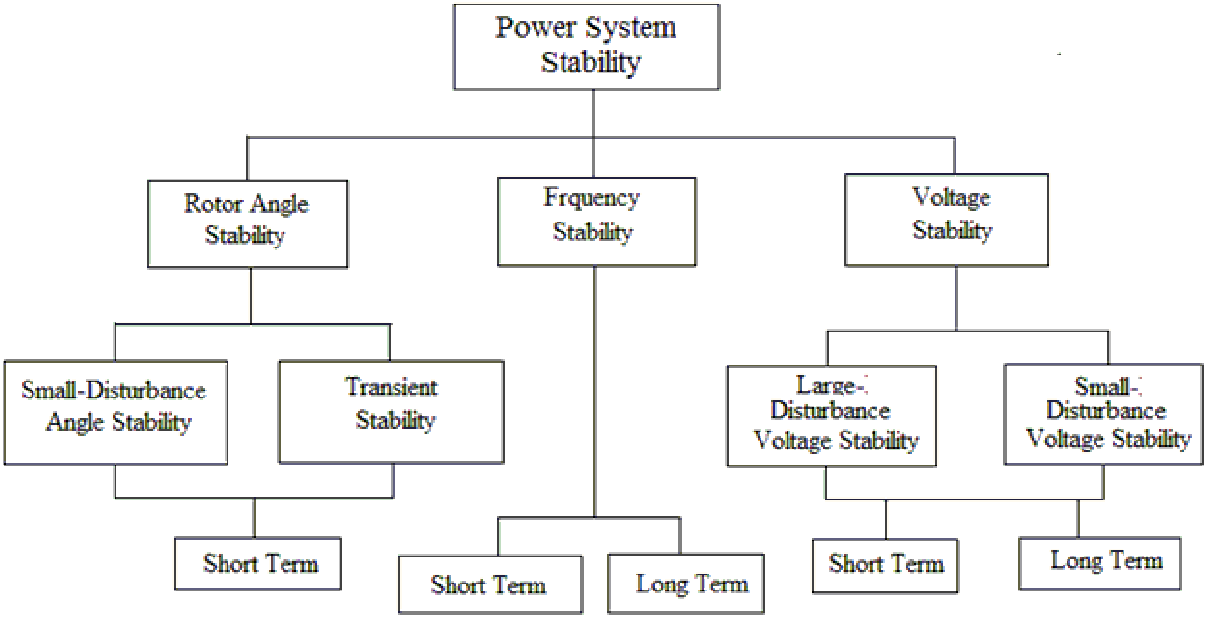


Fig. 1. **Classification of Power System Stability**

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operating conditions that violate field current limit.

It is useful to classify voltage stability into the following subcategories

- Large-disturbance voltage stability refers to the system’s ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, discrete controls and protections.
- Small-disturbance voltage stability refers to the system’s ability continuous controls, and discrete controls at a given instant of time. Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

This paper proposes the fuzzy logic controlled bridge type FCL to improve the transient stability of multi-machine power systems. To the best of our knowledge, there is no application of any nonlinear controller for the bridge type FCL. So far, the bridge type FCL has been applied to stability improvement in wind generator system and single machine power system [14], [15]. But, there is no report available on the bridge type FCL application to the transient stability improvement of multi-machine power system. Another salient feature of this work is that, the transient stability performance of the fuzzy logic controlled bridge type FCL is compared with that of another static non-linear controlled bridge type fault current limiter.

Moreover, instead of conventional reclosing, we considered the total kinetic energy based optimal reclosing of circuit breakers [6], [11], [13], [23] along with the fuzzy logic controlled bridge type FCL for improving the transient stability of the multi-machine power systems.For demonstrating the effectiveness of the proposed fuzzylogic controlled bridge type FCL in transient stability enhancement,the IEEE 30-bus power system model [25], [26] hasbeen used. Both balanced and unbalanced permanent as well astemporary faults are considered. Simulations are performed byusing the MATLAB/SIMULINK software.

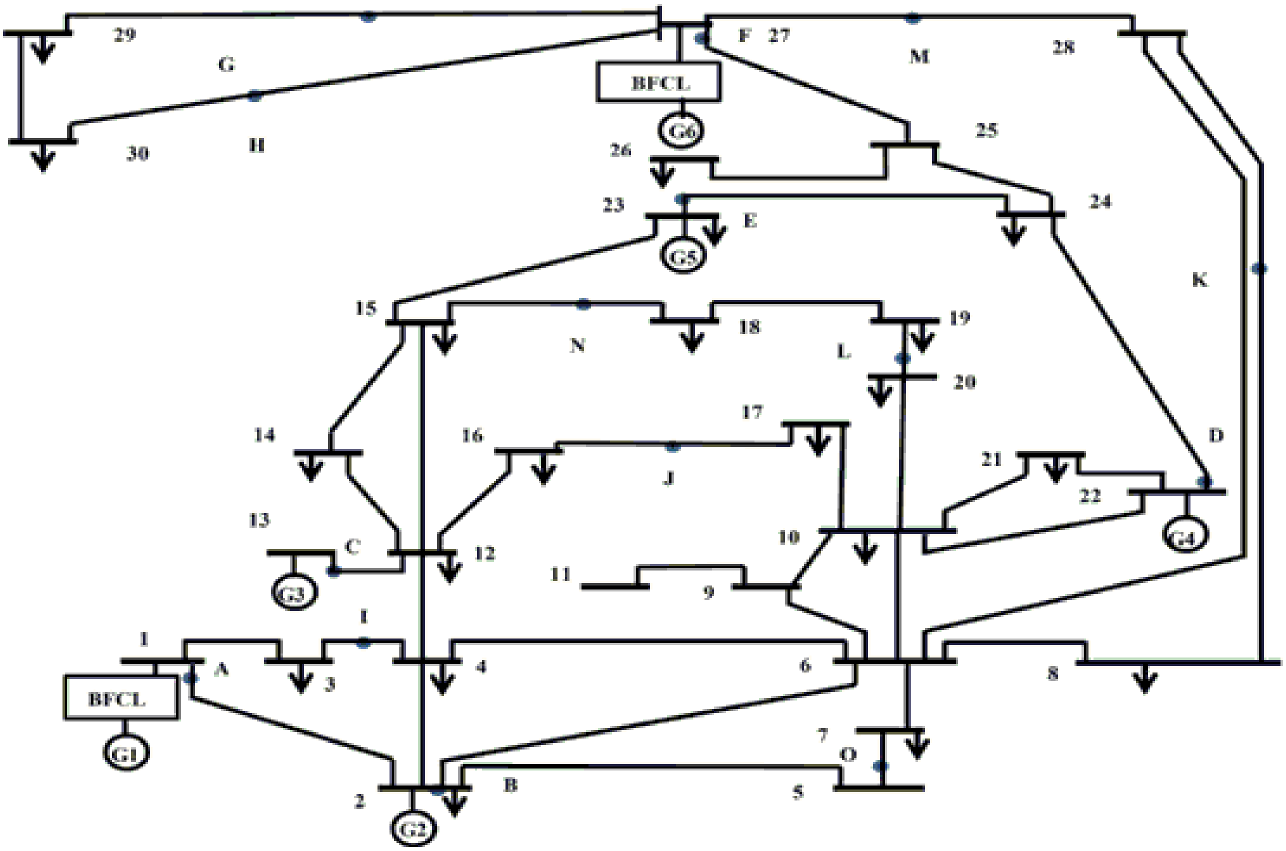


Fig. 2. IEEE – 30 Bus System with BFCL

## II. MODEL SYSTEM

For the simulation of the transient stability, the IEEE 30-buspower system [25], [26] model shown in Fig. 2 is used. The test system consists of six generating units interconnected with 41 branches of a transmission network to serve a total load of 189.2 MW and 107.2 MVAR. There are 24 loads and 4 transformers in the whole system. The system base is 100 MVA and 60 Hz. Three buses are rated 135 KV and the rest of the buses are rated33 KV [25], [26]. For the generators we have used the IEEE type 1 synchronous machine excitation and governor system [27]. The bridge type FCL is placed at the PCC points of generator 1and generator 6 as represented in Fig. 2. The reason of choosing those positions is described in the next subsections.

### A. IEEE 30-Bus Power System Behavior and Characteristics

In this work, extensive simulations have been carried out. From the speed and load angle responses in the event of faults, we got some important findings. The concept of coherency [28]–[30] was implemented for the generators in the system and we got two coherent groups as described in the next sub section. We carried out 15 fault points from A to O in the whole system to see the adverse fault locations. For quantifying these results we used the total kinetic energy based stability index [6], [11], [31], [32]. The details about this index are given in Section VII. Tables IV and V represent those index values. Lower index values represent a more stable system. From the index values and the total kinetic energy responses, we noticed fault location A and F are the most severe locations for that system.

Furthermore, if we consider both balanced and unbalanced faults near the terminals of generators 2 to 5 (fault points B, C D, and E), then the generator at which terminal we are considering fault gets accelerated and the effect on the rest of 5 generators is less. For example, if we consider a 3LG fault at the terminal of generator 4 (fault point D), then its steady operation hampers and the rest of the generators in the system are little affected. These characteristics of the system help in installing the BFCL in suitable locations, which is described in the following section.

### *B. Optimal Locations of BFCL and Their Impact*

In this work, the concept of coherency [28]–[30] is used to determine the optimal location of BFCL. From the load angle responses it was obvious that the generators 1 and 2depict a similar characteristic and they are coherent generators.

The rest of the generators (generators 3 to 6) in the system also exhibit the same characteristics and they are another coherent group of generators. Using this coherency property, we implemented2 BFCL in the two coherent groups. Moreover, considering the stability index values we placed the BFCL nearby the points A and F as represented in Fig. 2.

A fault can happen anywhere and anytime in the power systems. To know whether the implemented BFCLs are sufficient enough or not, we checked their effects on stability for all mentioned fault locations. Simulation results indicate that, if a fault happens at point A, then obviously a BFCL is needed near that location. The same conclusion is applicable to the fault location F. Now, for other fault locations, from the simulations we concluded that, if a fault happens near the location of coherent group 1 (generators 1 and 2), then only the BFCL near the location A is enough to make the system stable. Similarly, if a fault happens at the location of coherent group 2 (generators 3 to 6), then a BFCL near the location F is enough to make the system stable. Moreover, for some fault locations away from these two coherent groups, the system is numerically stable.

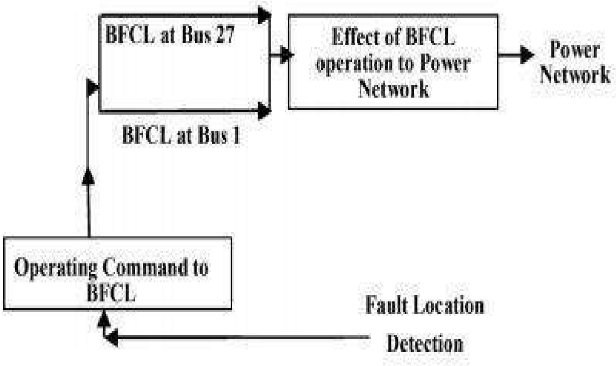


Fig. 3. BFCL Selection scheme

Therefore, for the IEEE 30-bus system, physically two BFCL always needed to be present at locations A and F. The fault location detection and BFCL activation scheme is presented in Fig. 3. The fault location detection is a very much matured field of study and it can be detected in a number of ways. Fault location can be detected by utilizing the electrical quantity or fault contour map or by using wave detected devices [33]–[35]. De-pending on the fault location technique, BFCL operation initiation signals will be generated in the central controller using suit-able algorithms. Those BFCL operation initiation commands will initiate the operation of either the fuzzy logic controlled BFCL at Bus 27 or fuzzy logic controlled BFCL at Bus 1. The input for the BFCL selection scheme in Fig. 3 will be digital signal (either 1 or 0). That signal will be generated in the central controller depending upon the fault location. Digital signal 1 will connect a BFCL in the power system and digital signal 0 will disconnect it from the power system.

## III. CONTROL DEVICE

### *A. Bridge Type Fault Current Limiter*

The bridge type FCL inserts resistance and inductance in the event of fault. It has the advantage that it does not need to have the characteristics for its operation [14], [15]. Thus it reduces the cost [14], [15].

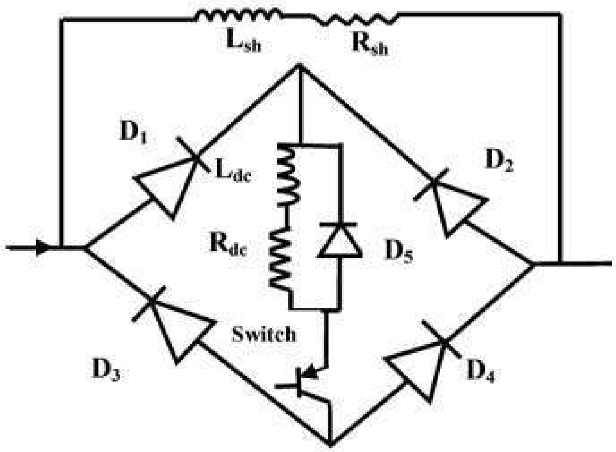


Fig. 4 Bridge type fault current limiter.

The bridge type FCL basically has two parts as shown in Fig. 4. The bridge part includes a diode rectifier bridge, a small dc limiting reactor along with a very small resistor ,an IGBT/GTO based semiconductor switch and a free wheeling diode. On the other hand, the main part consists of a resistor and an inductor as a shunt branch [14],[15]. In normal operation, the IGBT switch remains on and the line current for the positive half cycle passes through, semiconductor switch and. For the negative half cycle, the line current passes through, semiconductor switch and.. In this operation, the is charged to the peak of the line current and behaves like a short circuit and there is a negligible voltage drop.

In this work, the operation of the BFCL switch is controlled by the total kinetic energy deviation (TKED) of the generators. At the beginning of the fault, the total kinetic energy deviation varies and the line current increases to a higher value, but the dc reactor limits its increasing rate and protects the IGBT/GTO switch from severe change. When the total kinetic energy deviation change becomes very abrupt, the IGBT switch turns off and the shunt impedance comes in series with the faulted line. This series impedance limits the fault current to an acceptable limit. The freewheeling diode is used to provide a free route of dc reactor current as soon as the IGBT switch turns off[14], [15]. After the removal of the fault, the IGBT switch turns on again and the bridge type FCL resumes its normal operation. The detailed control scheme of the BFCL is described in the next section.

### *B. Closed Loop Control Scheme of BFCL*

Fig. 5 represents the connection scheme of the proposed fuzzy logic controlled bridge type fault current limiter in the power systems. As mentioned earlier, the bridge type fault current limiter is connected at the point of common coupling (PCC) points of generator 1 and generator 6 of the IEEE 30-bus power system. The reason behind its position is described in Section II. For switching the BFCL, the total kinetic energy deviation of the generators is used as the input signal for the fuzzy logic controller. The fuzzy logic controller is designed to produce varying shunt resistance as its output. This is because the shunt resistance is the most crucial part in proper fault current limiting ability of the BFCL. The output from the fuzzy logic controller is varying in nature because of the variation of the TKED. This shunt resistance value is then passed through a limiter to keep the value within 1 pu. Then a comparator circuit is used to generate proper switching signal for the IGBT switch. It is worthy to mention here that the switch operation is designed in such a way that it will turn on only when the gate signal is 1or more. On the other hand, it remains off when the gate signal is less than 1.

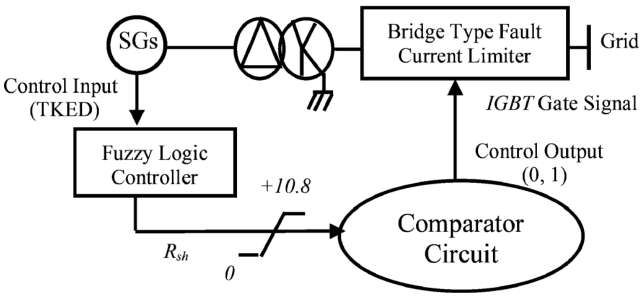


Fig. 5. Fuzzy logic controller connection scheme with bridge type FCL.

### *C. Bridge Type Fault Current Limiter Design Consideration*

Power systems are nonlinear in nature, and there are always load variations. So, determining the proper values of the shunt impedance is needed. In this work, the proper values of and within the limit are found out by parametric analysis of peak fault current and speed variation. In order to design the rectifier bridge and have parameter analysis, the behavior of BFCL was investigated both in normal and fault conditions. During normal operation, each line carries equal amount of power. To continue the normal operation or to ensure the least disturbance at fault, the BFCL should consume most of the power. The shunt impedance only carries current during fault current limiting mode, during which a voltage that equals to the amplitude of system line-to-line voltage is applied to the impedance and limited fault current flows through it. This means the bypass impedance dissipates the majority of fault energy. Therefore, the power stress on shunt resistor would be

$$P_{BFCL} = I^2_{fault} * Z_{sh} \qquad (1)$$

$$Z_{sh} = V_L / I_{fault} \qquad (2)$$

Where is the predefined fault current level is the power consumed by the BFCL, is the peak to peak line voltage, and is the BFCL shunt path impedance. The optimal value for the shunt path was approximated for each line using the above equations to be approximately 1 pu. The value of the limiting shunt path of the BFCL is kept the same for both the normal and fault conditions Table I represents the determined values for BFCL. Rectifier diodes are designed to carry the systems normal operating current. The IGBT switch was designed considering it carries the operating dc current in normal operation. Moreover, the voltage stress on the IGBT switch becomes peak in the event of fault. The system line to line voltage is applied across the IGBT.

TABLE I
BFCL PARAMETERS

| Parameters | Values |
|---|---|
| Bridge Type Fault Current Limiter | $L_{dc}$=0.01H,$R_{dc}$= 0.05Ω,<br>$L_{sh}$= 0.05H, $R_{sh}$= 10.8Ω |

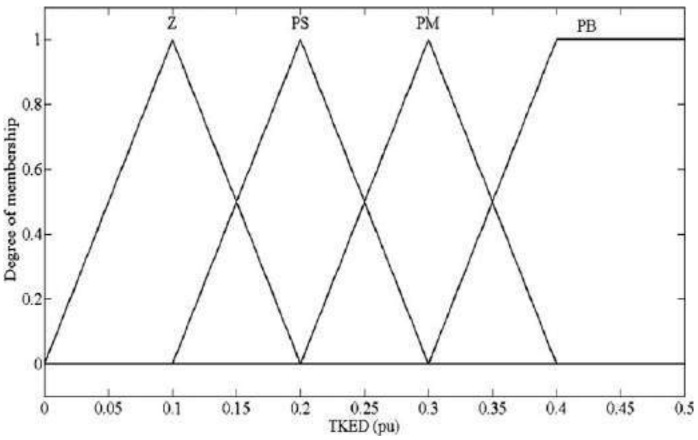


Fig. 6. Membership functions for TKED.

## IV. DESIGN OF FUZZY LOGIC CONTROLLER

The design of the proposed fuzzy logic controller (FLC) is described in the following:

### *A. Fuzzification*

For the design of the proposed fuzzy logic controller, deviationof total kinetic energy of synchronous generators, TKED [23], and shunt resistance of BFCL, , are selected as the input and output, respectively. Triangular membership functions for TKED are shown in Fig. 6, in which the linguistic variables Z, PS, PM, and PB stand for Zero, Positive Small, Positive Medium, and Positive Big, respectively. The membership functions have been determined by trial and error approach in order to obtain the best system performance. The equation of the triangular membership function used to determine the grade of membership values is as follows [23], [24], [37]:

$$\mu_{Ai}(\text{TKED}) = 1/b(b - 2|\text{TKED} - a|) \qquad (3)$$

where $\mu_{Ai}$ (TKED) is the value of grade of membership, "$b$" is the width, "$a$" is the coordinate of the point at which the grade of membership is 1, and "$x$" is the value of the input variable.

*A. Fuzzy Rule Base*

The specific feature of the proposed fuzzy controller is its very simple design having only one input variable and one output variable. The use of single input and single output variable makes the fuzzy controller very straightforward [2], [23].The control rules of the proposed controller are determined from the view point of practical system operation and by trial and error and are shown in Table II. A comparator circuit is used just after the fuzzy logic controller. The logic in the comparator circuit was put in such a way that, if the value of is less than 7 ohm, then a switch signal to IGBT was set to 1. If the value of $R_{sh}$ is greater than 7 ohm, then the IGBT gate signal was set to 0.

TABLE II
FUZZY RULE TABLE

| TKED (pu) | Rsh (ohm) |
|---|---|
| Z | 2 |
| PS | 4 |
| PM | 7 |
| PB | 10.8 |

*C. Fuzzy Inference*

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method [37] has been utilized. According to Mamdani's method, the degree of conformity, $W_i$, of each fuzzy rule is as follows:

$$W_i = \mu_{Ai}(\text{TKED}) \qquad (4)$$

*D. Defuzzification*

The Center-of-Area method is the most well-known and rather simple defuzzification method [24] which is implemented to determine the output IGBT switching value. This is given by the following expression:

$$Z = \sum W_i C_i / \sum W_i (5)$$

where is the crispy output function and $C_i$ is the value of defined in the fuzzy rule table.

## V. DESIGN OF STATIC NONLINEAR CONTROLLER

In this work, in order to evaluate the performance of the pro-posed coordinated operation of the fuzzy logic controlled bridge type fault current limiter and optimal reclosing in more detail, alternative static nonlinear controller is also considered [13]. The static nonlinear controller can be represented by a simple equation shown in (6):

$$R_{sh} = R * (\text{TKED})^2 \ (6)$$

Fig. 6 shows the block diagram of the static nonlinear controller [13]. The optimal value of the controller parameter is 0.024. This optimal value is determined by trial and error method. As we used a simple nonlinear controller, the value of the controller constant has paramount effect on the operation of the nonlinear controller controlled BFCL. We noticed if the value of is beyond some range, then the performance of BFCL changes rapidly. That range is given in the next paragraph. It is important to note that the same parameter is used throughout the simulations. Again, the comparator operation is designed in the same way as for the fuzzy logic controller. The IGBT switch will turn on only when the gate signal is 1. On the other hand, it remains off when the gate signal is less than 1.

For designing the nonlinear controller, the TKED square of the generators in the system is multiplied with a controller constant . The reason behind multiplying with is, without any constant , the TKED variation will be very abrupt and out of control. Moreover, the square of TKED is chosen as it represents a very simple nonlinear controller. From our observation we came to a very important decision about choosing the value for $R$ . We observed that has a range of value beyond which the system becomes unstable and out of control. In concrete form, the range of $R$ is

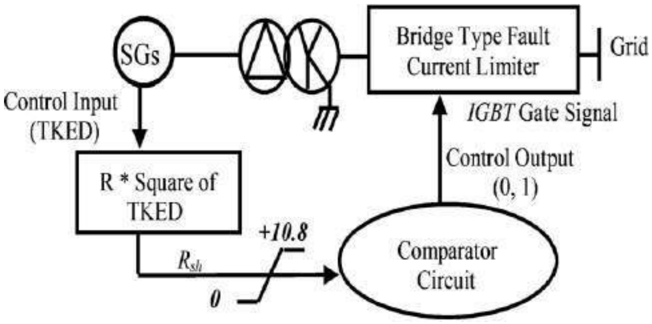


Fig. 7. Static nonlinear controller connection scheme with bridge type FCL.

$$0.024 \leq \text{R} < 0.055 \text{ (approximately).}$$

If we decrease the value of from higher to lower, then the system performance becomes better. On the other hand, beyond the lower limit, the system becomes unstable due to the over compensation of the controller. The controller constant is used to limit the high variation of TKED in the controller. The lower the value of will be, the less abrupt the TKED variation will be, as is multiplied with the TKED square in the controller. Therefore, in this work, we observed that beyond the lower limit of the range of , the variation of TKED becomes trivial and it has a steady response within the limit of the limiter in the next stage. Thus the nonlinear controller has a steady response and it degrades the BFCL operation if we choose a value of beyond the lower limit. Similarly, if we increase the value of from lower to higher, the performance of the BFCL degrades. If the value of increases beyond the higher limit of the controller constant's range, then due to higher abruption of the TKED variation the BFCL's operation degrades and the whole system becomes unstable.

## VI. OPTIMAL RECLOSING TECHNIQUE

Conventional auto-reclosing of circuit breakers can affect the stability, as it is dependent on the generator state of reclosing instances. So, to enhance the transient stability, circuit breakers should be closed at an optimal reclosing time (ORCT), when the system disturbance has no effect after reclosing operation.

Like our previous work [6], [11], in this work we have used the total kinetic energy based ORCT method. In this method, the time when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum is determined as ORCT [6], [11], [31], [32]. The optimal reclosing should happen when the deionization time, where cycles and KV indicates the line-to-line rms voltage of the system [6], [11].

Using the proposed optimal reclosing technique, the ORCT values among the 15 fault locations are shown in Table III.

## VII. SIMULATION RESULTS AND DISCUSSION

In this work, simulations are performed by using the Matlab/Simulink software. Simulations have been carried out considering both balanced (3LG: three-phase-to-ground) and unbalanced (1LG: single-phase-to-ground) permanent and temporary faults. Fifteen fault points from A to O as shown in the IEEE 30-bus power system model system of Fig. 2 have been considered. The simulation time and time step are considered as 20 s and 50 s, respectively.

### *A. Transient Stability Analysis for Permanent Fault*

Permanent fault persists for a substantial time in the power system. It is assumed that the circuit breakers open after 0.0833 s of the fault initiation, reclose according to the ORCT time as given in Table III, and reopen after 0.0833 s of the reclosing time.

Fig. 8 show the generators total kinetic energy responses for 3LG permanent fault at position I in the IEEE 30-bus power system. From the total kinetic energy responses it is clear that the fuzzy logic controlled bridge type FCL as well as static nonlinear controlled bridge type FCL makes the system stable.

However, the performance of the bridge type FCL is better than that of the bridge type FCL.

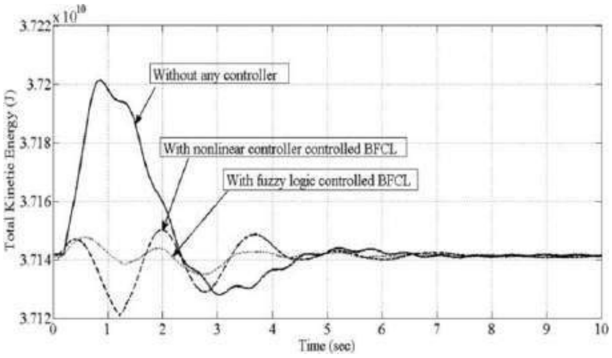
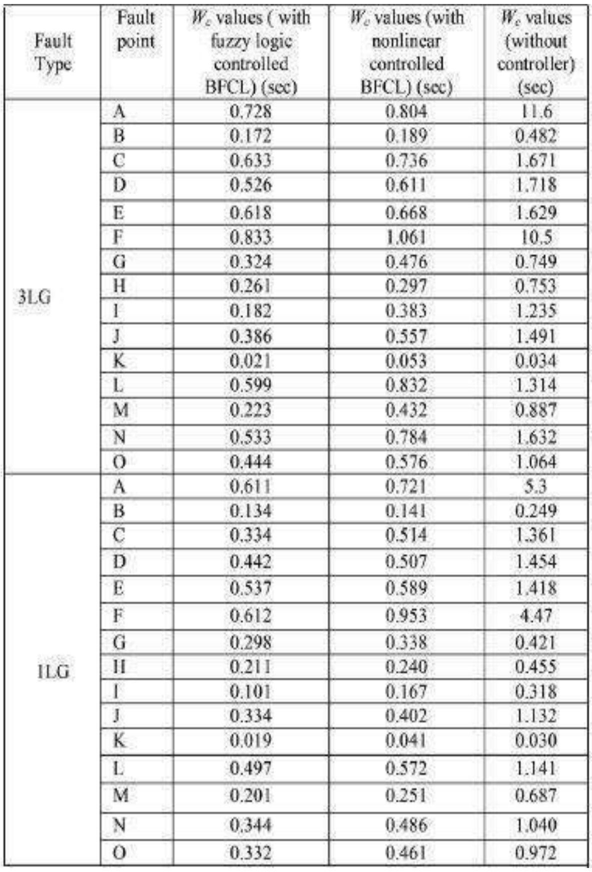


Fig. 8. Total kinetic energy response for 3LG permanent fault at position I.

For the evaluation of transient stability in this work we have used total kinetic energy based stability index, [6], [11], [31], [32], which is given by

TABLE IV

VALUES OF WITH FUZZY LOGIC CONTROLLED BFCL AND NONLINEAR CONTROLLED BFCL FOR PERMANENT FAULT



| Fault Type | Fault point | $W_c$ values ( with fuzzy logic controlled BFCL) (sec) | $W_c$ values (with nonlinear controlled BFCL) (sec) | $W_c$ values (without controller) (sec) |
|---|---|---|---|---|
| 3LG | A | 0.728 | 0.804 | 11.6 |
| | B | 0.172 | 0.189 | 0.482 |
| | C | 0.633 | 0.736 | 1.671 |
| | D | 0.526 | 0.611 | 1.718 |
| | E | 0.618 | 0.668 | 1.629 |
| | F | 0.833 | 1.061 | 10.5 |
| | G | 0.324 | 0.476 | 0.749 |
| | H | 0.261 | 0.297 | 0.753 |
| | I | 0.182 | 0.383 | 1.235 |
| | J | 0.386 | 0.557 | 1.491 |
| | K | 0.021 | 0.053 | 0.034 |
| | L | 0.599 | 0.832 | 1.314 |
| | M | 0.223 | 0.432 | 0.887 |
| | N | 0.533 | 0.784 | 1.632 |
| | O | 0.444 | 0.576 | 1.064 |
| 1LG | A | 0.611 | 0.721 | 5.3 |
| | B | 0.134 | 0.141 | 0.249 |
| | C | 0.334 | 0.514 | 1.361 |
| | D | 0.442 | 0.507 | 1.454 |
| | E | 0.537 | 0.589 | 1.418 |
| | F | 0.612 | 0.953 | 4.47 |
| | G | 0.298 | 0.338 | 0.421 |
| | H | 0.211 | 0.240 | 0.455 |
| | I | 0.101 | 0.167 | 0.318 |
| | J | 0.334 | 0.402 | 1.132 |
| | K | 0.019 | 0.041 | 0.030 |
| | L | 0.497 | 0.572 | 1.141 |
| | M | 0.201 | 0.251 | 0.687 |
| | N | 0.344 | 0.486 | 1.040 |
| | O | 0.332 | 0.461 | 0.972 |

where $T$ is the simulation time and $W_{total}$ is the total kinetic energy. The lower the value of , the better the system's performance is. Table IV shows the index values for 3LG and 1LGpermanent faults at 15 fault locations in the IEEE 30-bus power system. The values of the indexes indicate the effectiveness of the fuzzy logic controlled bridge type FCL for enhancing the transient stability.

However, the performance of the fuzzy logic controlled bridge type FCL is better than that of the static non-linear controlled bridge type FCL.

TABLE V
VALUES OF $W_c$WITH FUZZY LOGIC CONTROLLED BFCL AND NONLINEAR CONTROLLED BFCL FOR TEMPORARY FAULT

| Fault Type | Fault point | $W_c$ values ( with fuzzy logic controlled BFCL) (sec) | $W_c$ values (with nonlinear controlled BFCL) (sec) | $W_c$ values (without controller) (sec) |
|---|---|---|---|---|
| 3LG | A | 0.628 | 0.792 | 11.3 |
| | B | 0.142 | 0.169 | 0.472 |
| | C | 0.605 | 0.678 | 1.533 |
| | D | 0.488 | 0.527 | 1.452 |
| | E | 0.587 | 0.593 | 1.437 |
| | F | 0.777 | 0.939 | 9.91 |
| | G | 0.301 | 0.371 | 0.694 |
| | H | 0.243 | 0.291 | 0.751 |
| | I | 0.174 | 0.367 | 1.116 |
| | J | 0.380 | 0.501 | 1.431 |
| | K | 0.022 | 0.019 | 0.031 |
| | L | 0.543 | 0.571 | 1.231 |
| | M | 0.179 | 0.423 | 0.872 |
| | N | 0.303 | 0.617 | 1.143 |
| | O | 0.283 | 0.476 | 0.993 |
| 1LG | A | 0.601 | 0.692 | 5.1 |
| | B | 0.121 | 0.137 | 0.215 |
| | C | 0.337 | 0.441 | 1.260 |
| | D | 0.387 | 0.487 | 1.357 |
| | E | 0.315 | 0.464 | 1.042 |
| | F | 0.374 | 0.512 | 4.11 |
| | G | 0.226 | 0.345 | 0.411 |
| | H | 0.197 | 0.202 | 0.431 |
| | I | 0.085 | 0.149 | 0.278 |
| | J | 0.316 | 0.374 | 1.133 |
| | K | 0.020 | 0.032 | 0.030 |
| | L | 0.287 | 0.407 | 0.803 |
| | M | 0.180 | 0.221 | 0.677 |
| | N | 0.233 | 0.411 | 1.014 |
| | O | 0.266 | 0.374 | 0.961 |

## *B. Transient Stability Analysis for Temporary Fault*

It is assumed that the temporary fault persists for 0.5 s. The circuit breakers open after 0.0833 s of the fault initiation and recloses according to the ORCT time as given in Table III. Table V shows the index values for 3LG and 1LG temporary faults at 15 fault locations in the IEEE 30-bus power system. The stability indices indicate the effectiveness of the fuzzy logic controlled bridge type FCL in enhancing the transient stability. However, the performance of the fuzzy logic controlled bridge type FCL is better than that of the static nonlinear controlled bridge type FCL in improving the transient stability of the power system. Fig. 9 shows the generators total kinetic energy responses for 1LG temporary fault at position I in the IEEE 30-bus power system.

Moreover, we also checked the stability improvement performance of BFCL by observing the generator terminal voltage and PCC grid current where the BFCL is connected. Fig. 10 rep-resents the terminal voltage (rms value) of generator 6 for a 3LGtemporary fault at position F for different operating conditions. Similarly, Fig. 11 represents the rms current at grid point 27 for3LG temporary fault at position F for different operating conditions. From these responses it is clear that fuzzy logic controlled BFCL improves the generator voltage sag condition and reduces the effect of high fault current in the grid.

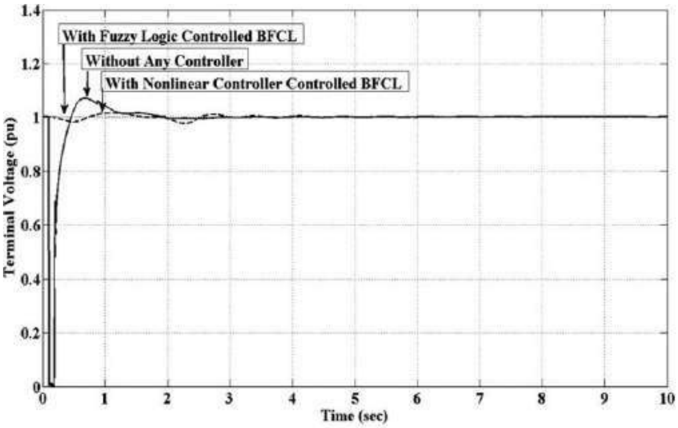


Fig. 9. Terminal voltage of generator 6 for 3LG temporary fault at position F

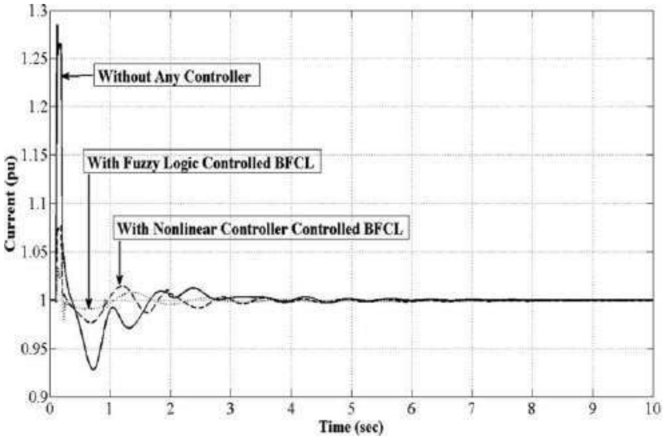


Fig. 10. Current at grid point 27 for 3LG temporary fault at position F.

### *C. Critical Clearing Time (CCT)*

In this work, the critical clearing time (CCT) has been considered and adopted as a stability limit for the power system from a practical point of view. The CCT presents the maximum allowable time at which a fault must be cleared to preserve and maintain the stability of the whole system [38]. With proper CCT information, a better coordination between the protective devices in a power system can be established. Lower CCT indicates less stable situation for power system transient stability studies [38]. For this study, a time domain simulation method is used to calculate the CCT. For the time domain simulation, a predefined step size is used for clearing time, and the stability of the system is observed. The Table VI represents the critical clearing times with and without controllers for 3LG permanent fault at different fault locations in the IEEE 30-bus test system. From Table VI it is clear that the CCT with nonlinear controlled BFCL is less than that with the fuzzy logic controlled BFCL, which is an indication of the superiority of the fuzzy logic controller over the static nonlinear controller for proper BFCL operation.

### D. *Cost Effectiveness*

The exact price of a bridge type FCL is not known, but the bridge type FCL has some distinct cost effective features. The bridge type FCL only requires diodes as a bridge and IGBT/GTO based switch which can be easily implemented commercially. With the advancement in semiconductor fabrication industry, current carrying and voltage withstanding capacity of diodes and IGBT switches are now higher compared to past days [22]. Moreover, the bridge type FCL has both inductance and resistance as a current limiting part and they are non-superconducting in nature. So, the excessive cost for implementing superconductor is reduced in bridge type fault current limiter. Moreover, the fuzzy logic controllers are not expensive [39]–[41]. Also, the membership functions and fuzzy rules in the proposed fuzzy logic controller are simple, easy to implement and thus avoids any complexity in implementation.

TABLE VI
CRITICAL CLEARING TIME WITH FUZZY CONTROLLED BFCL AND NONLINEAR CONTROLLER CONTROLLED BFCL FOR DIFFERENT FAULT LOCATIONS

| Fault Type | Fault point | CCT values without any controller (sec) | CCT values with Nonlinear Controlled BFCL (sec) | CCT values with Fuzzy Logic Controlled BFCL (sec) |
|---|---|---|---|---|
| 3LG | A | 0.121 | 0.158 | 0.169 |
| | B | 0.542 | 0.588 | 0.603 |
| | C | 0.402 | 0.447 | 0.476 |
| | D | 0.565 | 0.592 | 0.616 |
| | E | 0.572 | 0.591 | 0.628 |
| | F | 0.132 | 0.161 | 0.166 |
| | G | 0.614 | 0.665 | 0.698 |
| | H | 0.632 | 0.663 | 0.694 |
| | I | 0.513 | 0.581 | 0.617 |
| | J | 0.511 | 0.550 | 0.577 |
| | K | 0.712 | 0.757 | 0.796 |
| | L | 0.488 | 0.517 | 0.558 |
| | M | 0.723 | 0.789 | 0.808 |
| | N | 0.431 | 0.460 | 0.489 |
| | O | 0.505 | 0.531 | 0.578 |

### E. *Implementation Feasibility of Proposed BFCL Method*

The proposed methodology can be implemented in real practice. The input signal for the fuzzy logic controller for the pro-posed method will be collected via global positioning system (GPS) [6], [11], [31], [32] as represented in Fig. 12, where the GPS receiver receives the digitalized speed signal from the generators. The central control office then can determine the TKED easily. The GPS is very accurate, reliable and flexible to use with the phasor measurement systems. The synchronized measurement of power system units is viable using the GPS. Every power system has a margin of time delay for signal collection, accumulation and transmission. According to the literature, this time delay should not be more than 300 ms. In one of the previous works [3], the time delay margin in the power system is discussed. In that work, it is also discussed about the effect of the time delay on the power systems overall stability performance. That work concludes that, if the time delay is not within the delay margin for the system then it will deteriorate the whole system performance. The BFCL selection scheme that we proposed in this work will collect the signal from the power system and process them in a central control office as presented in Fig. 11.Then the processed signal will be sent back in the power system. Therefore, the BFCL selection scheme that we proposed in this work will introduce some delays in the system. This is a natural delay and inherent nature of the system and it cannot be avoided. In this work, to determine the delay margin, we introduced time delay in the TKED signal to the synchronous generator. We introduced time delay from 50 ms to 300 ms and noticed that the systems performance deteriorates after 260ms of time delay. Therefore, the total time delay in the system including the delay introduced in the BFCL selection scheme should not be more than 260 ms. If the time delay is more than that margin, then some measures should have to be taken to re-duce the negative effect of that delay. This is communication delay issue in the power system and there are works [42] on reducing the communication delay. We will also discuss about that phenomenon in our future work.

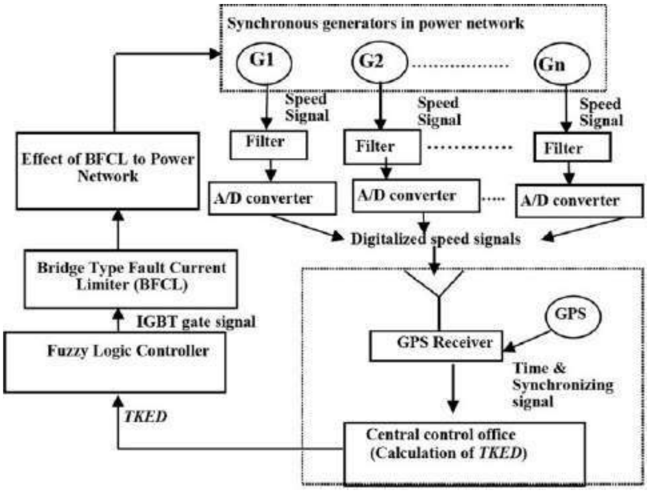


Fig. 11. Closed-loop control system of the fuzzy logic controller including GPS function.

## VIII. CONCLUSION

This paper proposes the application of fuzzy logic controlled bridge type FCL for improving the transient stability of multi-machine power systems. The performance of the fuzzy logic controlled bridge type FCL is compared with that of the static nonlinear controlled bridge type FCL. From the simulation plots and index values, the following conclusions can be drawn.

a) The proposed fuzzy logic controlled bridge type FCL can improve the transient stability of the multi-machine power systems.
b) The transient stability performance of the fuzzy logic con-trolled bridge type FCL is better than that of the static non-linear controlled bridge type FCL.

Therefore, the proposed fuzzy logic controlled bridge type FCL can be considered as an effective means for transient stability enhancement in multi-machine power systems.

In our future work we would like to address the communication delay problem and propose solutions to reduce the negative effect of delay. Moreover, we also would like to explore other types of fault current limiters for power system transient stability enhancement. Also, since the proposed fuzzy logic controller will handle input and output signals, during signal trans-mission there might be possible cyber-attacks or hacking. In the future, possible cyber vulnerabilities of the fuzzy logic controller considering its cyber physical architecture and the solutions will be studied.

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