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# Fault current limiter of VSC-HVDC systems using variable resistive bridge controller

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A B S T R A C T

This paper proposes a fuzzy logic controller (FLC) based variable resistive bridge type fault current limiter (VR-BFCL) to minimize the impact of faults on voltage source converter high voltage direct current (VSC-HVDC) systems. FLC for VR-BFCL is developed to dynamically insert the appropriate current limiting resistance during contingencies to maintain the fault currents within the acceptable limit. The proposed controller effectively provides variable duties to generate and insert controllable resistance in the system based on fluctuation of direct current (DC) link voltage and point of common coupling (PCC) voltage. The efficacy of the proposed controller is justified through simulations work for balanced and unbalanced faults. The results demonstrate that oscillations in PCC voltage and DC link voltage can be maintained within the acceptable range by controlling fault current through the insertion of the appropriate resistance. It is also found that the proposed controller outperforms the existing method.


## 1. Introduction

The generated power in power generating unit is transmitted to the load center through high-voltage direct current (HVDC) conversion due to minimizing power losses, improving security and reliability. Furthermore, renewable several energy generation units, such as offshore wind farm generator, and solar photovoltaic (PV), integration with HVDC system provides better flexibility compared to conventional high voltage alternating current (HVAC) system due to independent control of active and reactive power[1]. Among the different renewable sources, the variable speed wind generators can be integrated to the electric network through the voltage source converter (VSC) based conversion system [2]. Mainly, two types of HVDC networks are proposed based on converter topologies: the line commutated converter (LCC) and the VSC. However, the later one is considered better over the former one as it provides more flexibility in controlling power and DC voltage, and improved power quality[3–5].

Hitherto, for VSC–HVDC transmission system, different VSC topologies, such as two–level, three–level neutral point clamped, and multi–level, are proposed in different works [6,7]. Although VSC-HVDC system has several benefits, AC/DC faults on such system pose serious threats, and consequently it can lose synchronism from the rest of the systems. The reason is that the VSC topology has antiparallel diodes and it requires large DC capacitor which can be discharged sharply during abnormal conditions [8]. In case of short-circuit faults, current in VSC-HVDC increases sharply within few milliseconds which causes high current flow to the DC link through the antiparallel diodes of VSC and may damage the converters [9,10]. Furthermore, the DC link voltage, and the point of common coupling (PCC) voltage deviate from the nominal values due to several faults in HVDC network. The improvement of PCC and DC link voltage deviations of offshore wind farm connected VSC-HVDC is presented in [11] with hybrid optimization based proportional integral (PI) controller. Among the several methods proposed in the literature to resolve fault problems of VSC-HVDC system, employing fault current limiters (FCLs) is considered to be the best one [12]. Fault current limiters can restrict high fault current during the response time of a circuit breakers [13]. As a result, current interruption stress on a circuit breaker

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| *2LG* | Double line to ground fault |
| *3LG* | Three line to ground fault |
| *BFCL* | Bridge type fault current limiter |
| *D* | Duty cycle |
| *FFF* | Feed forward function |
| *FLC* | Fuzzy logic controller |
| *FRT* | Fault ride through |
| *HVDC* | High voltage DC |
| *IGBT* | Insulated gate bipolar transistor |
| *LCC* | Line commutated converter |
| *MTDC* | Multiterminal HVDC |
| *PCC* | Point of common coupling |
| *PI* | Proportional integral |
| *PLL* | Phase locked loop |
| *VR* | Variable Resistive |
| *VSC* | Voltage source converter |

*Subscripts*

| | |
|---|---|
| *aceff* | Effective value in AC side |
| *d* | Direct axis |
| *max* | Maximum |
| *mes* | Measured |
| *min* | Minimum |
| *q* | Quadrature axis |
| *ref* | Reference |
| *var* | Variable |

is reduced with the FCLs, which eventually minimizes the size and cost of the circuit breaker.

Different types of FCLs, such as flux coupling, magnetic, resistive, hybrid, superconducting and non-superconducting, are extensively applied in power system; however, superconduc-ting[14–17] and nonsuperconducting[18–20] types are more dominant. In [21], a new DC reactor superconducting FCL is presented, which has reduced coil rating. Nevertheless, the presented structure does not have the flexibility to vary coil resistance, which is imperative due to the fact that the fault current varies over a wide range during contingencies. In order to address this issue, another DC coil based non-superconducting FCL is proposed in [22] which restricts the fault current efficiently than the one presented in [21]; however, the problem with this structure is that it faces significant voltage drop in the coil. Besides, to resolve the fault problems of VSC-HVDC system and improve stability, different categories of superconducting FCL (SFCLs) [23–25] are also examined in the literature. Although the application of superconducting FCLs does not require any additional control circuit, it has several disadvantages as compared to non-superconducting FCLs, such as bulky size, high cost, overweight, magnetic interference, loss in normal mode, and prolonged recovery time [26,27]. An efficient non-superconducting variable resistive bridge type fault current limiter (VR-BFCL) is proposed and studied for several branches of power system to overcome the issues of stand-by mode loss, non-adaptable resistance and high cost [28–30]. However, the application, control, and design of this new topology are not fully investigated yet in VSC-HVDC system considering the system non-linearities. The VR-BFCL structure has flexibility and options to insert varying resistance by designing proper control signals which can improve the performance of the system greatly. However, a detailed design is a challenging task due to non-linearity in the system. Thus, fault ride through (FRT) improvement of VSC-HVDC with proper controller design, including varying nature of VR-BFCL and system non-linearities, presents a potential solution to the fault problems. To fill-up this gap, in this paper, VR-BFCL with non-linear fuzzy logic based control strategy is proposed for FRT augmentation of VSC-HVDC system. A detailed fuzzy logic controller is proposed to control VR-BFCL in order to insert varying resistance, which is dynamically controlled based on the PCC voltage deviation and DC link voltage fluctuation, between the grid and VSC. The proposed controller has two main advantages: it is superior over conventional fixed duty controller and easy implementation is achieved even with the consideration of system non-linearities. A comparative study is also performed to show the superiority of the designed non-linear FLC controller over the conventional fixed duty based control approach. The system and associated controllers are implemented in MATLAB Simulink environment. The main contributions of the proposed works can be summarized as below.

- VSC-HVDC system with VR-BFCL is modeled for controlling fault currents to facilitate analysis.
- The resistive value of VR-BFCL is properly designed considering pre-fault and post post-fault analysis.
- Non-linear FLC for VR-BFCL is designed to reduce fault currents. The design process involves the consideration of varying PCC and DC link voltages to generate variable duties, which are overlooked in the previous studies.
- Several fault current impacts on the controller are analyzed to observe the effectiveness of the proposed controller. The balanced and unbalance faults are considered to study the effect of the designed controller.
- The DC voltage oscillation is reduced with the proper design of the non-linear controller. Furthermore, the voltage profile at PCC is greatly improved with the proposed controller based VR-BFCL which is dynamically controlled by the adaptive duty.

The rest of paper is organization as follows. Section 2 describes the architecture, working principle, and design method of VR-BFCL. The system modeling, HVDC controller design, and the proposed FLC based VR-BFCL controllers are presented in Section 3. Efficacy of the proposed controller is described in Section 4 by conducting case studies. The feasibility study of VR-BFCL is performed in Section 5. Finally, Section 6 concludes the work. .

## 2. Variable resistive current limiter design

In this work, fuzzy logic control based on VR-BFCL, which dynamically inserts impedance to restrict fault current and improve stability, is proposed. The basic construction and working principle of VR-BFCL are described in Fig. 1.

The VR-BFCL is constructed with isolation transformers, diodes, inductor, resistor and an insulated gate bipolar transistor (IGBT) switch [28,29,31,32] as shown in Fig. 1. The main current limiting part of VR-BFCL is constructed with a parallel resistor and IGBT switch. The proposed controller keeps the IGBT switch turned on in normal condition which eventually bypasses the resistor, thus, $L_{DC}$ works as short-circuit and charges to peak value. The addition of small valued $L_{DC}$ in series with $R_{var}$ limits the drastic current change, thus, it protects the IGBT from large $di/dt$.

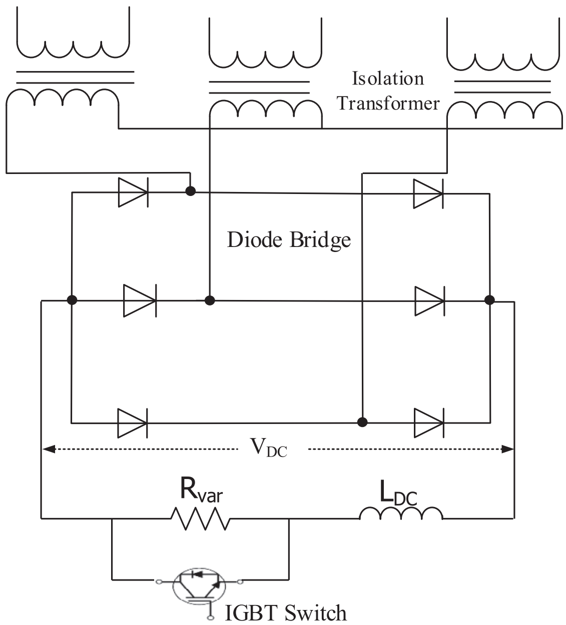



**Fig. 1.** Variable resistive bridge type fault current limiter (VR-BFCL).

The DC voltage across the diode bridge of VR-BFCL can be depicted by the equation below [28].

$$V_{DC} = \frac{6}{\pi}\sin(\frac{\pi}{3})kV_m \tag{1}$$

where $k$ represents turn ratio of transformer, $V_m$ represents the peak voltage in the primary side of transformer. The relationship of the variable resistance ($R_{var}$), duty, and the DC resistance is given by the following equations.

$$R_{DC} = (1-D)R_{\text{var}} \tag{2}$$

$$\frac{3(V_m/\sqrt{2})^2}{R_{aceff}} = \frac{\{\frac{6}{\pi}\sin(\frac{\pi}{3})kV_m\}^2}{R_{DC}} \tag{3}$$

Following equation can be obtained by further simplification of the above equation.

$$R_{aceff} = \frac{\pi^2}{18k^2}R_{DC} \tag{4}$$

This is clear from this expression that the total effective resistance appeared in the primary side of the isolation transform, which is in series with the line, mainly depends on turn ratio of the isolation transformer and DC resistance $R_{DC}$. Furthermore, $R_{DC}$ depends on the duty cycle of the IGBT switch and $R_{var}$, thus, by dynamically controlling the duty cycle, $R_{aceff}$ can be controlled. Therefore, the main purpose of the work is to design non-linear fuzzy logic controller, which dynamically adapts the duty to insert a varying effective resistance in the HVDC system to protect it from high current during disturbances as well as improve dynamic performance.

The systematic VR-BFCL design process is followed in this work. The proper value of resistance insertion can mitigate the impact of fault on the system. To achieve this goal, in the design process, it is assumed that the VR-BFCL should consume at least equal or greater active power of the system capacity during fault condition. If the system power exchange capacity is $P_{exch}$, then the power consumption by each phase of VR-BFCL can be expressed as follows. However, this expression is based on the assumption of a balanced three phase fault on the system. Since, in general, the balanced fault is considered more severe than unbalanced faults.

$$P_{VR-BFCL} \geqslant \frac{P_{exch}}{3} \tag{5}$$

The post-fault power consumption capability of VR-BFCL is given by the following equation.

$$P_{VR-BFCL} = \frac{V_{PCC}^2}{R_{aceff}} \tag{6}$$

where, $V_{PCC}$ is the voltage at the PCC. By simplifying Eq. 4 to 6, following equation is obtained.

$$\frac{V_{PCC}^2}{R_{aceff}} \geqslant \frac{P_{exch}}{3} \tag{7}$$

Further simplification of the above equation gives the following expression for calculating the proper value of DC resistance ($R_{DC}$) of VR-BFCL.

$$R_{DC} \leqslant \frac{54k^2}{\pi^2}\frac{V_{PCC}^2}{P_{exch}} \tag{8}$$

So, the Eq. 8 is the basis for calculation of the proper value of DC resistance of VR-BFCL based on PCC voltage, power exchange between the grids, and isolation transformer turns ratio in case of balanced fault. However, since the inequality presents in the Eq. 8, in order model the unbalanced faults, the trial and error method is applied to find the value of $R_{DC}$ for VR-BFCL.

## 3. System modeling and controller design

The schematic diagram of two terminal VSC-HVDC is shown in Fig. 2. In order to demonstrate the performance of the proposed controller, this works implements a simple two-terminal VSC-HVDC system, connecting two grids of the same operating frequency. One of the terminals controls the power flow between two grids by changing reference power command, while the other one controls the DC link voltage. Both the VSCs, for terminal one and terminal two, has inner current controllers, which are designed to control the powers. The detailed design process of the fuzzy logic controller and the design of the VSC controller are documented in the following subsections.

### 3.1. Control of VSC1

As shown in Fig. 2, the VSC1 controller helps to maintain the desired active power flow through the HVDC link. The active and reactive powers ($P_s$ and $Q_s$) can be expressed in terms of direct and quadrature axis voltages and currents as below.

$$P_s = \frac{3}{2}[V_dI_d + V_qI_q] \tag{9}$$

$$Q_s = \frac{3}{2}[-V_dI_q + V_qI_d] \tag{10}$$

Since the synchronization device, phase locked loop (PLL), continuously forces the voltage ($V_q$) to zero, the above equations can be further simplified as follows.

$$P_s = \frac{3}{2}V_dI_d \tag{11}$$

$$Q_s = -\frac{3}{2}V_dI_q \tag{12}$$

Therefore, the reference currents of direct axis and quadrature axis are given by the equations below for controlling active and reactive power, respectively.

$$I_{dref} = \frac{2}{3V_d}P_{ref} \tag{13}$$

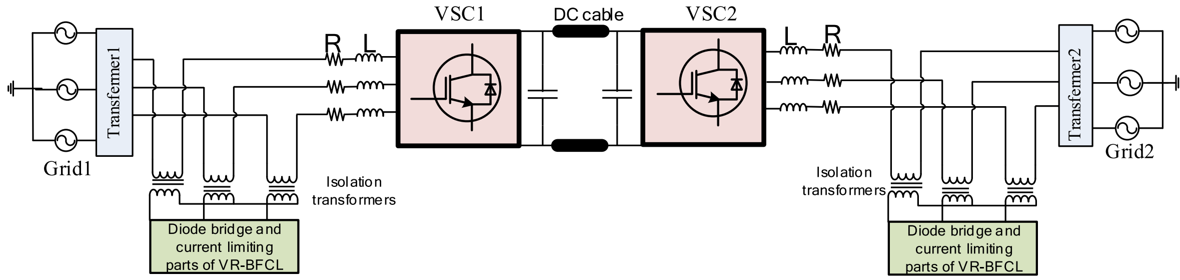



**Fig. 2.** VR-BFCL connection with the two-terminal HVDC network.

$$I_{qref} = -\frac{2}{3V_d}Q_{ref} \tag{14}$$

The VSC-HVDC system AC side and converter equations are given in $d-q$ frame as follows.

$$L\frac{dI_d}{dt} = L\omega_0 I_q - RI_d + V_{td} - V_d \tag{15}$$

$$L\frac{dI_q}{dt} = -L\omega_0 I_d - RI_q + V_{tq} - V_q \tag{16}$$

$$V_{td} = \frac{V_{DC}}{2}m_d \tag{17}$$

$$V_{tq} = \frac{V_{DC}}{2}m_q \tag{18}$$

Based on the above equations set (Eq. 13 to 18) and third harmonic injected PWM technique, the detail controller for VSC1 is developed as shown in Fig. 3. The adoption of the third harmonic injected PWM technique helps to minimize the required DC bus voltage, which, in turn, increases system stability. As shown in Fig. 3, active and reactive powers are controlled independently by controlling $d$-axis and $q$-axis currents, respectively. The proportional integral (PI) controllers are used for both the current controllers, and their parameters are obtained by pole zero cancellation technique in this work.

### 3.2. Control of VSC2

The control performance of VSC-HVDC system greatly depends on DC link voltage [33,34], which is controlled by one of the VSCs for two terminal HVDC system. In this study, VSC2 controller is designed to keep the DC link voltage to preset value. Thus, in addition to the current controller like VSC1, the controller of VSC2 employs an additional outer controller to control DC voltage. This outer controller adjusts the active power exchange with the capacitor employing a PI controller for properly controlling the DC voltage. Thus, the power provided by the outer controller is added with the power exchange between the grids to generate its reference power ($P_{ref2}$) as demonstrated in Fig. 4. It is worth mentioning that the PI for VSC2 is tuned with symmetrical optimum method as reported in [35].

### 3.3. Proposed fuzzy logic controller for VR-BFCL

Fuzzy logic controller (FLC), effective in case of non-linearity and difficulty in implementation of an exact mathematical model, is based on if-then rules. Since the power system is highly non-linear, and the non-linearity further increases during different disturbances, FLC based current limiter controller is proposed in this work. The principle of FLC and the proposed FLC design technique for VR-BFCL are documented in the following subsections.

#### 3.3.1. Principle of FLC

The FLC is non-linear controller having the capability to control real-world problems better than the linear controller. The FLC focuses to imitate the process followed by the human mind while executing control tasks. The FLC a is combination of four different steps such as fuzzification, rules, decision making, and defuzzification [36,37]. In the fuzzification step, the numerical input variable is converted into fuzzy sets whose elements have the degree of membership. The FLC rules have if-then structure to perform two important tasks: generating rules and inferring the output from these rules. The decision-making part selects rules from the rule base and their corresponding degree of firing. Finally, in the defuzzification step, the fuzzy output from the decision-making part converted to crisp values which are then passed to the physical actuator for controlling the plant.

#### 3.3.2. Fuzzification

In the proposed FLC controller, the normalized voltage deviations at the PCC and DC link are employed as input. Since

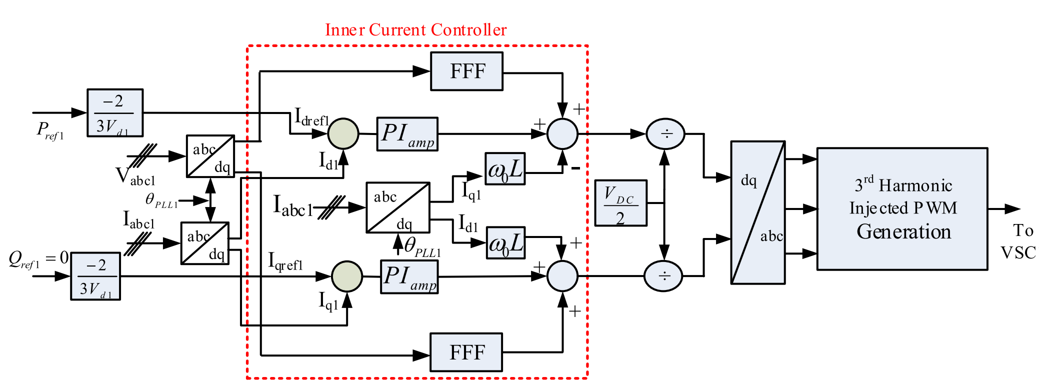



**Fig. 3.** The controller diagram of VSC1.

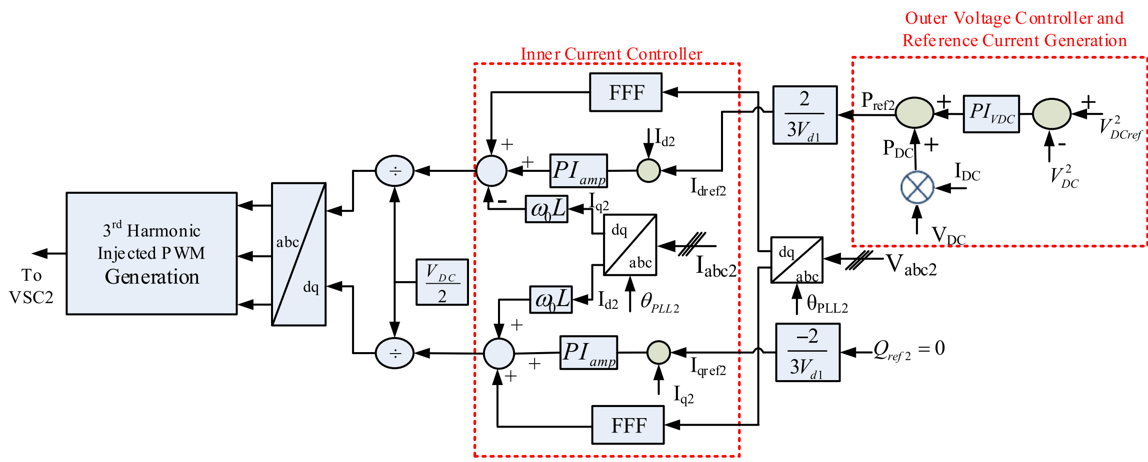


**Fig. 4.** Schematic diagram of controller of VSC2.

the performance of HVDC system greatly depends on the DC voltage control, the fuzzification process adopts the DC link voltage for adaptable duty generation. Triangular membership functions (MFs) are used for the both input and output variables of FLC as shown in Fig. 5.

It is worth mentioning that other membership functions were tried; however, those functions could not provide good transient stability of the system. In the design process, the system was tested under different severe faults, and deviations at PCC and DC link voltage are observed. Maximum voltage deviations for PCC and DC link were found 0.83 pu and 2.25 pu, respectively. The range of fuzzy variable, which is called the universe of discourse (UOD), is set from this observation. The fuzzy set, the ordered pairs of the membership function and UOD, is totally characterized by triangular membership function as shown in Fig. 5. The output variable is duty (D) that is varied from 0 to 1 in order to change the inserted resistance from zero to maximum value. Different linguistic variables are selected in the design process like NB, NS, Z, PS, PB which stands for negative big, negative small, zero, positive small, and positive big, respectively. The grade of membership values is determined from the following equation of the triangular membership function.

$$\mu_{Ai}(\Delta V_{PCC}/\Delta V_{DC}) = \frac{1}{b}\{b - 2|(\Delta V_{PCC}/\Delta V_{DC}) - a|\} \tag{19}$$

where $\Delta V_{PCC}/\Delta V_{DC}$ are input variables, $a$ is the point at which grade of membership is 1 and $b$ is the width of membership functions.

### 3.3.3. Fuzzy rule base

The fuzzy rule base is the heart of the fuzzy logic controlled system. The fuzzy rule based design process involves storing all possible combinations of input variables. DC link voltage deviation ($\Delta V_{DC}$) and PCC voltage deviation ($\Delta V_{PCC}$) are used as input variables to determine duty (D). Schematic diagram of fuzzy design is shown in Fig. 5.

All the fuzzy rules are listed in Table 1. The DC link and PCC voltage deviations are represented with different linguistic variables such as NB, NS, Z, PS, and PB. The range of these variables are determined with the applications and observations of severe faults in the HVDC network. The fuzzy rules are designed based on the these linguistic variables to generate duty for the VR-BFCL which are also represented by similar linguistic variables. For example, if the $\Delta V_{DC}$ and $\Delta V_{PCC}$ lie in PB MF due to the appearance of faults in the system, higher value of resistance should be inserted in series with the line to restrict the fault current. And,

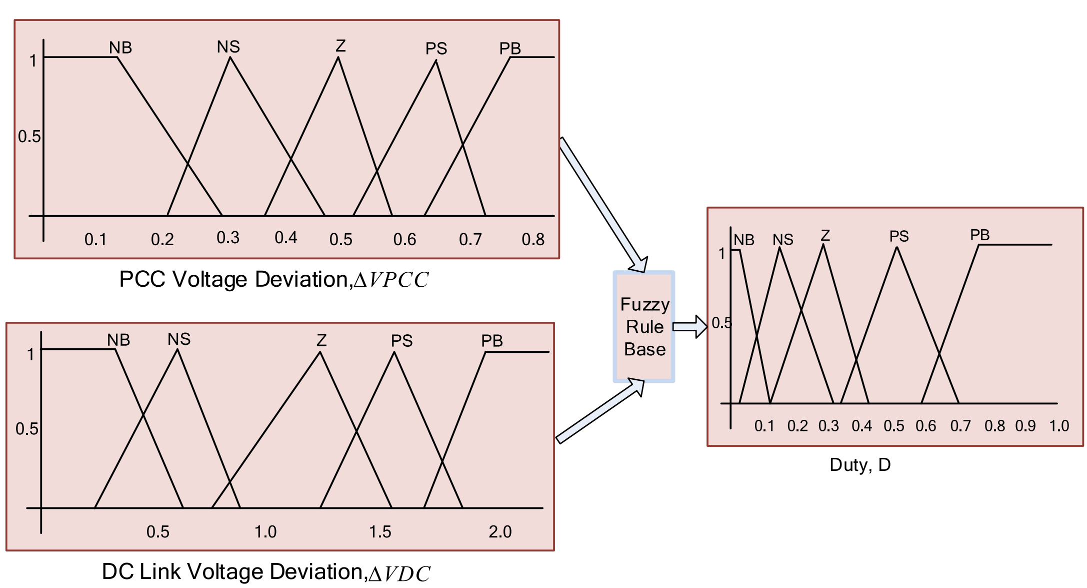



**Fig. 5.** Input and output membership functions of fuzzy system.

**Table 1**
Fuzzy rules for duty generation.

| | | $\Delta V_{PCC}$ | | | | |
|---|---|---|---|---|---|---|
| | | NB | NS | Z | PS | PB |
| $\Delta V_{DC}$ | NB | PB | PS | PS | Z | NS |
| | NS | PS | Z | Z | NS | NS |
| | Z | PS | Z | NS | NS | NS |
| | PS | Z | Z | NS | NS | NB |
| | PB | Z | NS | NS | NB | NB |

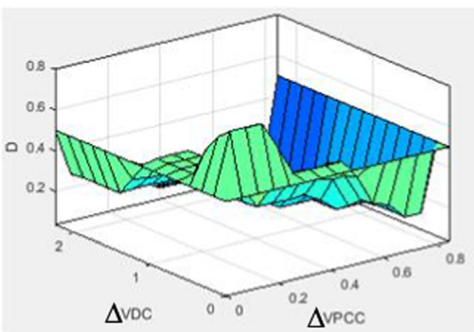



**Fig. 6.** Surface viewer of the proposed fuzzy control.

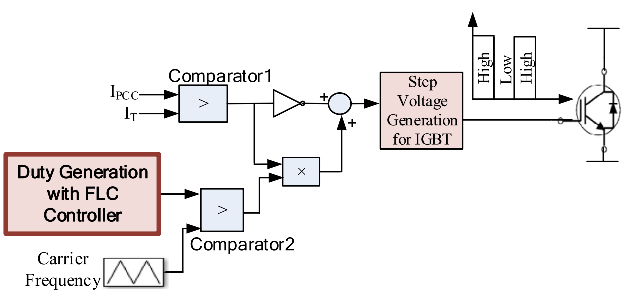



**Fig. 7.** Gate pulse generation for VR-BFCL with FCL strategy.

according to Eq. (2), lower value of duty (D) provides higher resistance. Therefore, at this condition D should be NB. Likewise, if the $\Delta V_{DC}$ and $\Delta V_{PCC}$ are within narrow range during the system faults, for example NB, the lower value of resistance of VR-BFCL can restrict the fault current. Thus, higher value of D is required at this condition which is given by the linguistic variable PB as shown in 1. All other rules as listed in Table 1 are extracted following the same process. The surface viewer of the proposed fuzzy controller are shown in Fig. 6. This figure illustrates that the variations in DC link and PCC voltages vary the duty cycle accordingly to insert varying current limiting resistance.

### 3.3.4. Fuzzy inference

In the proposed fuzzy logic controller, Mamdani method is used for the inference mechanism. Each fuzzy rule with the degree of conformity ($W_i$) is given by the following equation [38].

$$\sum W_i = \{\mu_{Ai}(\Delta V_{PCC})\}\{\mu_{Ai}(\Delta V_{DC})\} \tag{20}$$

where $\mu_{Ai}(\Delta V_{PCC})$ and $\mu_{Ai}(\Delta V_{DC})$ are the values of the grade of input variable memberships and $i$ is the number of rules.

## 3.4. Defuzzification

Among the different defuzzification methods, center of area [38] is used in this work to determine the crisp values of duty (D). According to center of area method, D is obtained as follows:

$$D = \left(\sum W_i L_i\right)/\left(\sum W_i\right) \tag{21}$$

where $L_i$ is the value of duty D, which has been expressed in terms of linguistic variables in Table 1.

This work employs the above non-liner fuzzy logic controller (FLC) to dynamically adjust the resistance of VR-BFCL in VSC-HVDC system. The implementation of the fuzzy controller is achieved with the proposed control circuit shown in Fig. 7. The control strategy employs two comparators: comparator1 for detecting the fault based on the PCC current [39,40] and comparator2 for activating fuzzy logic controller.

As shown in Fig. 7, during the normal operation, the output of comparator1 becomes low if the PCC current $I_{PCC}$ is lower than the threshold current $I_T$. Thus, one of the inputs to the product block is low which is multiplied with the output of comparator2.

**Table 2**
Parameters of VSC-HVDC system and its controller.

| Parameter | Value |
|---|---|
| Rated power of HVDC system | 110 MVA [t] |
| AC Grid voltage | 138 kV (L-L rms) |
| System Frequency | 60 c/s |
| Transformer voltage ratio | 138/52 kV (Delta/Y) |
| Transformer magnetizing resistance | 0.001 pu |
| Transformer magnetizing inductance | 0.001 pu |
| Resistor (R) | 40.6 mΩ |
| Reactor (L) | 10.8 mH |
| DC capacitor | 250 $\mu$F |
| DC voltage | 100 kV |
| $R_{var}$ | 330 mΩ |
| $L_{DC}$ | 10 mH |
| Inner, PI | 14.37 + 54.18/s |
| Outer, PI | 0.0219 + 0.5071/s |
| Feed forward function (FFF) | $1/(1 + 8.6 \times 10^{-6}s)$ |
| DC cable length | 200 km |
| DC cable resistance | 13.9 mΩ/km |
| DC cable capacitance | 23.1 $\mu$F/km |
| DC cable inductance | 0.159 mH/km [b] |

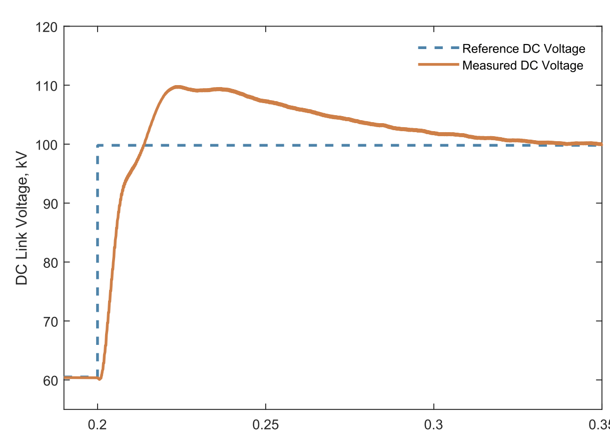



**Fig. 8.** Reference DC link voltage tracking performance.

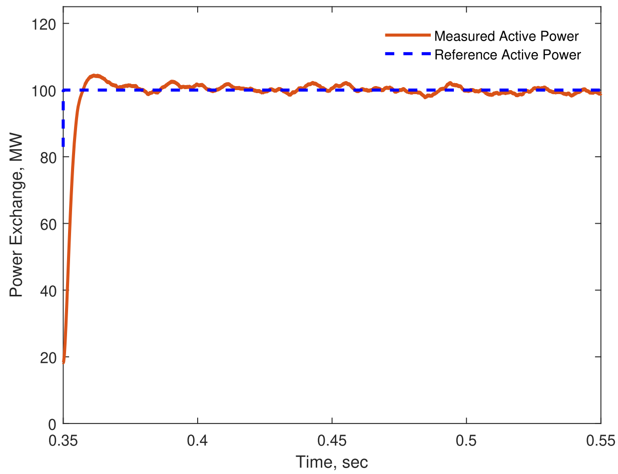
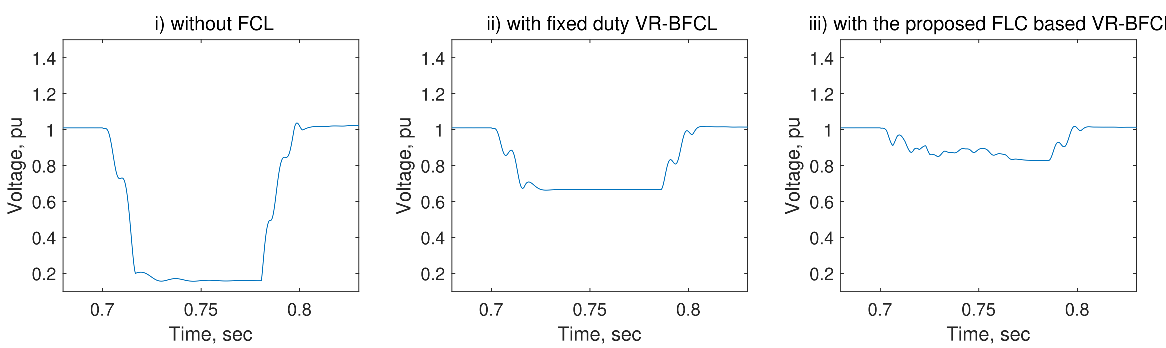



**Fig. 9.** Reference power tracking performance.

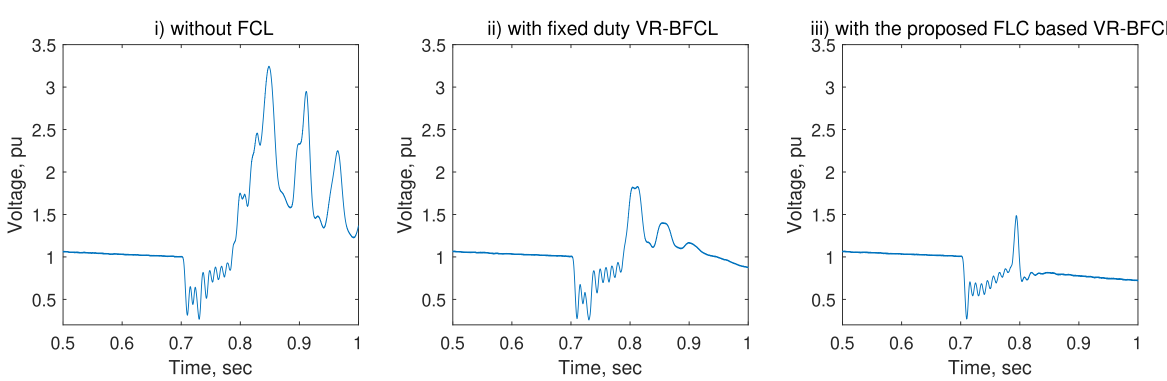
In this way, the fuzzy logic controller is bypassed and IGBT of VR-BFCL is kept turned on. However, during contingencies, $I_{PCC}$ exceeds the threshold current $I_T$ and output of the comparator1 becomes high. At this condition, the output of comparator2, which is the adjustable duty provided by the proposed fuzzy controller, is passed to the summation block by the product block. Thus, during a faulty condition, the IGBT of VR-BFCL is turned on and turned off in dynamic fashion based on the variable duty provided by the FLC controller.

## 4. Results and discussions

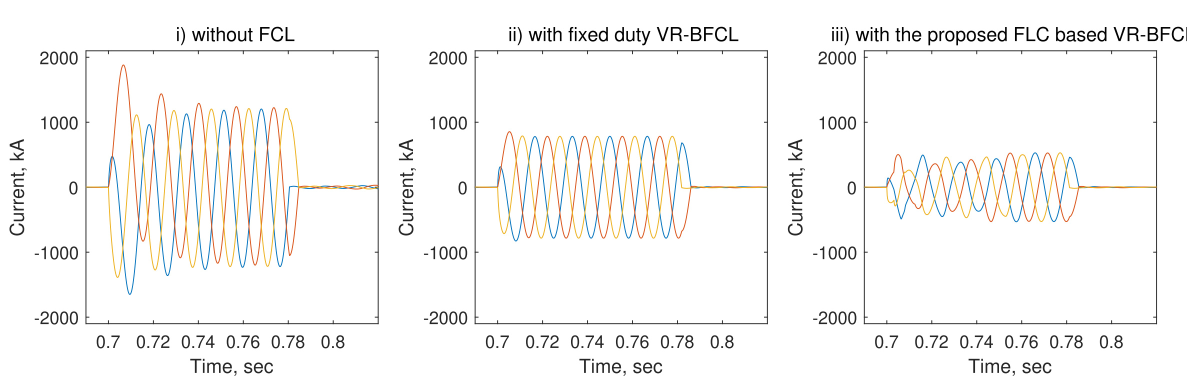
In this study, extensive simulations are conducted by applying various faults, symmetrical and unsymmetrical, in the systems. For all fault conditions, system performance in restricting fault current and augmenting stability is analyzed for three cases: without any auxiliary devices, with fixed duty based controller and with the proposed fuzzy logic controller.




(a) Voltage at PCC




(b) DC link voltage




(c) Line current

**Fig. 10.** System performance improvement with the proposed control strategy in response to symmetrical 3LG fault.

**Table 3**
Fluctuation reduction with proposed FLC based VR-BFCL for symmetrical 3LG fault.

| | Amount of fluctuation | | |
|---|---|---|---|
| Parameters | Without FCL | With fixed duty VR-BFCL | With Proposed FLC based VR-BFCL |
| PCC voltage (pu) | 0.8759 | 0.344 | 0.1895 |
| DC link voltage (pu) | 2.87 | 1.56 | 1.18 |
| Line Current (kA) | 1207 | 567 | 315 |

### 4.1. System and controller data

The test system as depicted in Fig. 2 and its associated controllers presented in Fig. 3 and Fig. 4 are built in MATLAB Simulink environment. The system and controllers parameters are listed in Table 2.

### 4.2. Simulation considerations

Initially, the DC link capacitors are gradually charged to some level, up to 61 kV, by the current flow to the capacitors through the antiparallel diodes of VSCs. Now, the reference voltage for the outer controller of VSC2 is step changed to 100 kV at 0.2 s. The DC link voltage tracking performance of the VSC2 is visualized in Fig. 8 by plotting both reference and measured voltages. It is observed that the DC link voltage has overshot around 110 kV; however, it settles to the reference value within a very short time, at around 0.33 s as shown in Fig. 8.

After the DC link voltage settles to its steady state value of 100 kV, the reference power command for VSC1 is changed to 100 MW in order to transfer this power from the grid one to the grid two as shown in Fig. 9. The settling time of active power is less than that of DC link voltage. The active power observes a negligible steady state error as shown in Fig. 9.

Now, the VSC-HVDC system is fully in steady state conditions, considering both the DC link voltage and active power exchange between two grids. At this conditions, several faults, for 6 cycles, are applied in the system to test the efficacy of the proposed nonlinear FLC based VR-BFCL controller. Three cases are simulated as below.

i. without FCL
ii. with fixed duty controller VR-BFCL
iii. with proposed fuzzy logic controller VR-BFCL

### 4.3. Symmetrical fault application

The most severe fault in power system is symmetrical three phase fault (3LG). The improvement in dynamic performance of the system, considering PCC voltage, DC link voltage, and line current, with the proposed controllers is depicted in Fig. 10 for symmetrical 3LG fault.

PCC voltage varies from 0.1611 pu to 1.037 pu without any auxiliary control approach. Application of fixed duty based control of VR-BFCL reduces PCC voltage fluctuation by 60.7%. However, the height level of performance is observed in reducing PCC voltage fluctuation with the proposed fuzzy logic control based VR-BFCL which is around 78.36%. DC link voltage also fluctuates over a wide range without any supplementary controller. Fixed duty based VR-BFCL slightly damps the DC link voltage oscillation corresponding to 47.3%. The proposed fuzzy logic control based VR-BFCL further reduces the DC link voltage fluctuation and 58.88% fluctuation reduction is observed. The performance improvement of the system with the proposed VR-BFCL control strategy is also observed by limiting line fault current as shown in Fig. 10. Table 3 represents the transient stability improvement of the VSC-HVDC system for symmetrical 3LG fault. The amount of fluctuation for three parameters, such as PCC voltage in p.u., DC link voltage in p.u., and the line current in kA, are presented in table 3. As shown in table 3, the deviations of all parameters are greatly reduced with the proposed controller as compared to the conventional controller.

The system performance improvement should be guaranteed with the parameters variations. The proposed controller is also tested with the variations of interface inductance ($L$) and resistance ($R$). Under the case of 3LG fault, the voltage at PCC is shown for in Fig. 11 for base case and 10% increase and decrease of $L$ and $R$. It is found that the variation of PCC voltage lies within the narrow range which guarantees the robustness of the proposed FLC based approach.

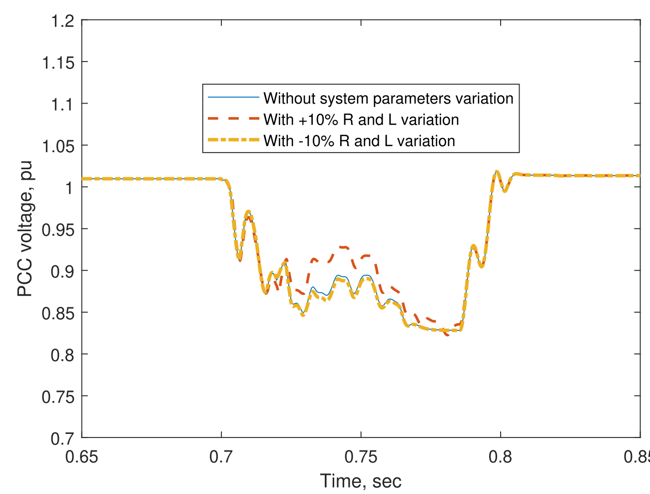



**Fig. 11.** Robustness of the proposed controller with system parameters variation.

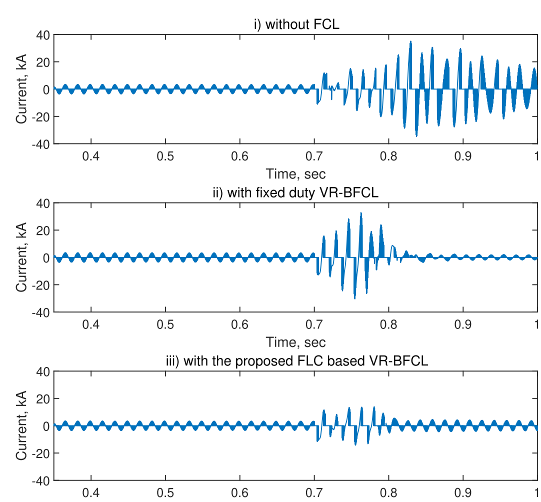
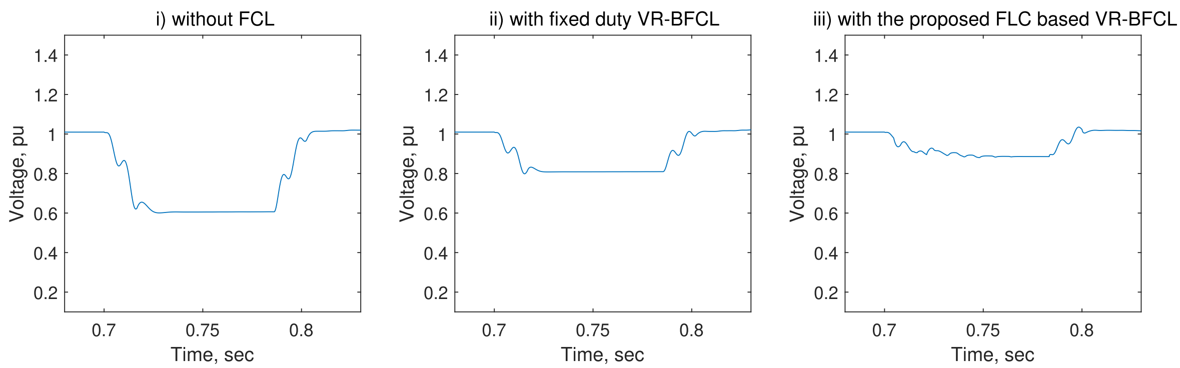
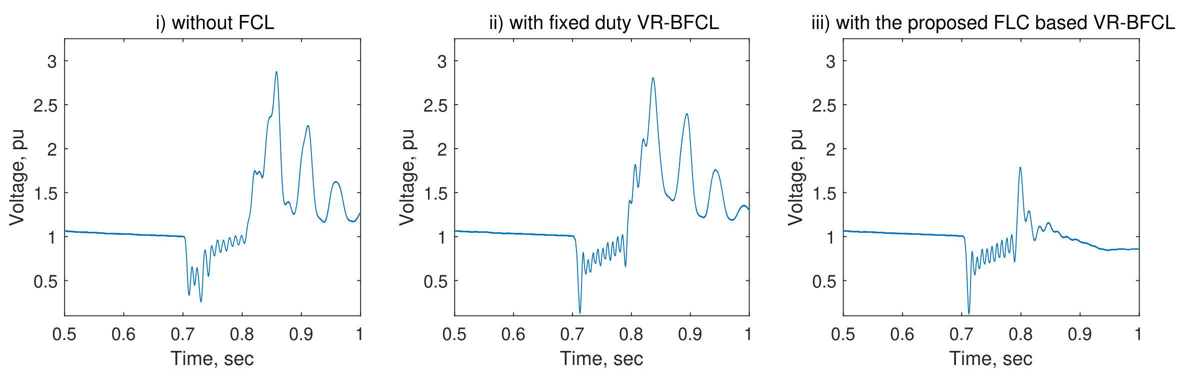


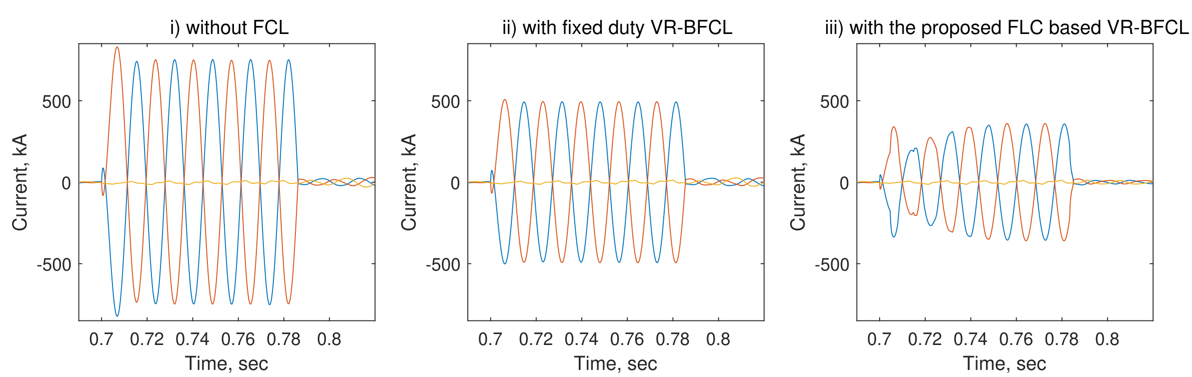

**Fig. 12.** Impact of grid fault on the power converter.




(a) Voltage at PCC




(b) DC link voltage




(c) Line current

**Fig. 13.** Performance improvement with the proposed control strategy in response to symmetrical 2LG fault.

**Table 4**
Fluctuation reduction with proposed FLC based VR-BFCL for symmetrical 2LG fault.

| | Amount of fluctuation | | |
|---|---|---|---|
| Parameters | Without FCL | With fixed duty VR-BFCL | With Proposed FLC based VR-BFCL |
| PCC voltage (pu) | 0.394 | 0.1912 | 0.1108 |
| DC link voltage (pu) | 2.595 | 2.56 | 1.53 |
| Line Current (kA) | 554 | 321 | 233 |

Furthermore, the proposed controller minimizes the negative impact of grid faults on the voltage source converter as depicted in Fig. 12. As shown in Fig. 12, the current through the IGBT switch of VSC1 is very high during the entire simulation time without any FCL. The IGBT switch current is slightly reduced with the fixed duty based control approach, while the proposed FLC based control keeps the IGBT current within safe limit and thus it protects the converters from damage.

### 4.4. Unsymmetrical fault application

In order to show the effectiveness of the proposed control strategy of VR-BFCL, unsymmetrical double line to ground (2LG) fault is also applied in the system as shown in Fig. 13. System performance is very poor in reducing PCC voltage fluctuation, DC link voltage fluctuation and fault current without any auxiliary controller as observed by simulation studies. As shown in Fig. 13, the voltage

**Table 5**
Percentage fluctuation reduction with proposed FLC based VR-BFCL for symmetrical and unsymmetrical fault.

| Percentage fluctuation reduction | | | | |
|---|---|---|---|---|
| | Symmetrical Fault | | Unsymmetrical Fault | |
| Parameters | With fixed duty VR-BFCL | With Proposed FLC based VR-BFCL | With fixed duty VR-BFCL | With Proposed FLC based VR-BFCL |
| PCC voltage | 60.7 | 78.36 | 51.47 | 71.8 |
| DC link voltage | 47.3 | 58.88 | 1.03 | 41.04 |
| Line Current | 53.02 | 73.9 | 42.05 | 57.94 |

at PCC varies between 0.6065 to 1.014 pu without fault current limiter. The VR-BFCL application in the system with fixed duty based control approach reduces the fluctuation of PCC voltage by only 51.47%. However, a great reduction in PCC voltage fluctuation is observed with the proposed FLC based fault current limiter which corresponds to 71.8% reduction in fluctuation. DC link voltage of the HVDC system also varies from 0.2495 to 2.845 pu. Fixed duty based VR-BFCL is applied in the system to reduce this DC link voltage fluctuation. Application of the fixed duty control reduces fluctuation by 1.03% only. Now, the proposed control approach of VR-BFCL reduces the DC link voltage oscillation by 41.04%. Table 4 represents the performance improvement of VSC-HVDC system with proposed fuzzy logic control based VR-BFCL for an unsymmetrical double line to ground (2LG) fault. As shown in table 4, the line current is very high, i.e. 554 kA, without any auxiliary controller. The application of conventional fixed duty controller reduces the fault current to 321 kA. However, the significant reduction in fault line current is observed with the proposed FLC based current limiter which corresponds to only 233 kA. Thus, the proposed technique is capable to protect the VSC and the associated devices from the exposure of high current.

Overall performance improved by the proposed fuzzy logic control based VR-BFCL is observed in the Table 5. As listed in Table 5, the proposed FLC based VR-BFCL is superior over traditional controller in minimizing voltage deviations at PCC and DC link, and line current, in case of both balanced and unbalanced faults. As observed in table 5, the maximum percentage reductions in PCC voltage are observed for both types of faults with the proposed controller. The percentage reductions in PCC voltage for 2LG and 3LG faults are 71.8% and 78.36%, respectively, with the proposed FLC based VR-BFCL controller.

## 5. Practical installation and cost of VR-BFCL

The actual cost of VR-BFCL is not known yet since this new topology is still in the research phase. Also, the actual installation cost varies depending on the capacity of this device. For example, the installation in the distribution level will have less cost compared to the cost of installation in high voltage transmission level. However, the installation cost can be assumed from the number of components needed for the fabrication of the device. For instance, diodes, resistor, inductor, power electronic switch, and transformers are needed to develop VR-BFCL. Thanks to the developments of power electronics, all the components are available in the market and cost can be calculated for installation in any level of the power system.

## 6. Conclusions

In this paper, a non-linear FLC based bridge controller is proposed to improve the dynamic performance of VSC-HVDC system. Depending on fault detection based on the PCC current, the controller is designed. Effective controllable resistance is generated and placed in the system during the disturbance depending on the amount of DC link and PCC voltage deviations. We have used Matlab Simulink to develop the FLC controller, HVDC system, and fault current limiter. The performance of the proposed controller is evaluated by applying several disturbances, such as symmetrical and unsymmetrical, in the system. Simulation results demonstrate that the proposed controller effectively restricts fault currents and augments transient response of the VSC-HVDC systems. The fluctuated voltage of DC link, and PCC is decreased remarkably and fault current is significantly reduced. The proposed method also ensures the system stability. It is also observed that the controller proposed outperforms the traditional fixed duty controller. However, the fault current controlling of off-shore wind farm integrated HVDC system is imperative. Thus, in our upcoming work, transient stability improvement of a large-scale wind farm integrated VSC-HVDC system will be considered with VR-BFCL.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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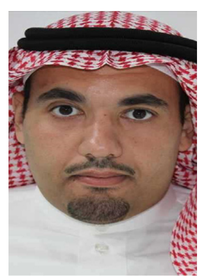

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