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FAULT TOLERANT VOLTAGE SOURCE CONVERTER FOR HVDC TRANSMISSION SYSTEM USING FUZZY LOGIC

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Abstract--**This paper proposes a new breed of high-voltage dc (HVDC) transmission systems based on a hybridmultilevel voltage source converter (VSC) with ac-side cascaded H-bridge cells. The proposed HVDC system offers the operational flexibility of VSCbased systems in terms of active and reactive power control, blackstart capability, in addition to improved ac fault ride-through capability and the unique feature of current-limiting capability during dc side faults. Additionally, it offers features such as smaller footprint and a larger active and reactive power capability curve than existing VSC-basedHVDC systems, including those usingmodular multilevel converters. To illustrate the feasibility of the proposed HVDC system, this paper assesses its dynamic performance during steady-state**Fuzzy LogicControl and **network alterations, including its response to ac and dc side faults.**

***Index Terms*—DC fault reverse blocking capability, hybrid multilevel converter with ac side cascaded H-bride cells, modular multilevel converter, voltage-source-converter high-voltage dc (VSCHVDC) transmission system fuzzy..**

I. INTRODUCTION

IN the last decade, voltage-source-converter high-voltagedc (VSC-HVDC) transmission systems have evolved fromsimple two-level converters to neutral-point clamped convertersand then to true multilevel converters such as modular converters. This evolution aimed to lower semi-conductorlosses and increase power-handling capability of VSC-HVDCtransmission systems to the level comparable to that of conventionalHVDC systems based on thyristor current-source converters,improved ac side waveform quality in order to minimizeor eliminate ac filters, reduced voltage stresses on convertertransformers, and reduced converter overall cost and footprint With increased demand for clean energy, power system networksneed to be reengineered to be more efficient and flexibleand reinforced to accommodate increased penetration ofrenewable power without compromising system operation andreliability.

A VSC-HVDC transmission system is a candidate to meetthese challenges due to its operational flexibility, such as provisionof voltage support to ac networks, its ability to operateindependent of ac network strength therefore makes it suitablefor connection of weak ac networks such as offshore windfarms, suitability for multi-terminal HVDC network realizationas active power reversal is achieved without dc link voltagepolarity change, and resiliency to ac side faults (no risk ofcommutation failure as with line-commutating HVDC systems). However, vulnerability to dc side faults andabsence of reliable dc circuit breakers capable of operatingat high-voltage restrict their application to point-to-pointconnection.Present VSC-HVDC transmission systems rely on their converterstation control systems and effective impedance betweenthe point-of-common-coupling (PCC) and the converter terminalsto ride-through dc side faults. With present converter technology,the dc fault current comprises the ac networks contributionthrough converter free-wheeling diodes and discharge currentsof the dc side capacitors (dc link and cable distributed capacitors)[23], [24]. The magnitude of the dc-side capacitorsdischarge current decays with time and is larger than the ac networkscontribution. For this reason, dc fault interruption mayrequire dc circuit breakers that can tolerate high let-through currentthat may flow in the dc side during the first few cycles afterthe fault, with high current breaking capacity and fast interruptiontime. Recent HVDC converter topologies with no commondc link capacitors, such as the modular multilevel converter(M2C), may minimize the magnitude and duration of the dischargecurrent first peak .

There are two approaches to assist VSC-HVDC transmissionsystems to ride-through dc side faults. The first approachis to use a fast acting dc circuit breaker, with considerably highlet-through current to tolerate the high dc fault discharge currentthat may flow in the dc side. This breaker must be capable ofoperating at high voltage and isolates temporary or permanentdc faults, plus have a relatively high-current-breaking capacity.R presents a prototype 80-kV dc circuit breakerwith dc current breaking capacity of 9 kAwithin 2ms.However,this first step is inadequate, as the operating voltage of present.

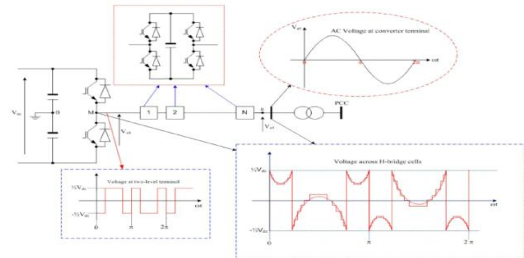

Fig. 1. Hybrid voltage multilevel converter with ac side cascaded H-bridge cells

VSC-HVDC transmission systems reach 640 kV pole-to-pole(or 320 kV for a bi-polar configuration), with power-handlingcapability of 1 GW. This breaker approach may introduce significant steady-state losses due to the semiconductors in themain current path.

The second approach is to use converter stations with dc faultreverse-blocking capability [1], [4], [23]. Each converter stationmust be able to block current flow between the ac and dc sidesduring a dc fault, allowing dc-side capacitor discharge current,which is the major component of the dc fault current, to decay tozero and then isolate the fault. Several converter topologies withthis inherent feature have been proposed, including an H-bridgemodular multilevel converter, an alternative arm modular multilevelconverter, and a hybrid multilevel converter with ac-sidecascaded H-bridge cells. However, the drawback is that the activepower exchange between the ac networks reduces to zeroduring the dc fault period.

Commensurate with the second approach, this paperpresents a new HVDC transmission systems based on ahybrid-voltage-source multilevel converter with ac-side cascadedH-bridge cells. The adopted converter has inherent dcfault reverse-blocking capability, which can be exploited toimprove VSC-HVDC resiliency to dc side faults. With coordinationbetween the HVDC converter station control functions,the dc fault reverse-blocking capability of the hybrid converteris exploited to achieve the following:

• eliminate the ac grid contribution to the dc fault, henceminimizing the risk of converter failure due to uncontrolledovercurrent during dc faults;

• facilitate controlled recovery without interruption of theVSC-HVDC system from dc-side faults without the needfor opening ac-side circuit breakers;

• simplify dc circuit breaker design due to a reduction in themagnitude and duration of the dc fault current; and

• improve voltage stability of the ac networks as converterreactive power consumption is reduced during dc-sidefaults.

Section II of this paper describes the operational principle andcontrol of the hybrid voltage source multilevel converter withac-side cascaded H-bridge cells.

Section III describes the HVDC system control design,specifically, ac current controller in synchronous referenceframe, dc link voltage, and active power, and ac voltagecontrollers. A detailed block diagram that summarizes howdifferent control layers of the proposed HVDC transmission system are interfaced is presented.

Section IV presents simulations of a hybrid converter HVDCtransmission system, which demonstrate its response duringsteady-steady and network disturbances. Included are simulationsof four quadrant operation, voltage support capability,and ac and dc fault ride-through capabilities.

II. HYBRID MULTILEVEL VSC WITH AC-SIDE CASCADEDH-BRIDGE CELLS

Fig. 1 shows one phase of a hybrid multilevel VSC withH-bridge cells per phase. It can generate voltagelevels at converter terminal “a” relative to supply midpoint“0.” Therefore, with a large number of cells per phase, theconverter presents near pure sinusoidal voltage to the convertertransformer as depicted in Fig. 1 [1]. The two-level converterthat blocks high-voltage controls the fundamental voltageusing selective harmonic elimination (SHE) with one notchper quarter cycle, as shown in Fig. 1. Therefore, the two-levelconverter devices operate with 150-Hz switching losses, hencelow switching losses and audible noise are expected. TheH-bridge cells between “M” and “a” are operated as a seriesactive power filter to attenuate the voltage harmonics producedby the two-level converter bridge. These H-bridge cells are controlledusing level-shifted carrier-based multilevel pulsewidthmodulation with a 1-kHz switching frequency. To minimizethe conversion losses in the H-bridge cells, the number of cellsis reduced such that the voltage across the H-bridge floatingcapacitors sum to. This may result in a small converterstation, because the number of H-bridge cells requiredper converter with the proposed HVDC system is one quarterof those required for a system based on the modular multilevelconverter. With a large number of cells per phase, the voltagewaveform generated across the H-bridge cells is as shownin Fig. 1, and an effective switching frequency per device ofless than 150 Hz is possible. The dc fault reverse-blockingcapability of the proposed HVDC system is achieved by inhibitingthe gate signals to the converter switches, therefore nodirect path exists between the ac and dc side through freewheeldiodes, and cell capacitor voltages will oppose any currentflow from one side to another. Consequently, with no currentflows, there is no active and reactive power exchange betweenac and dc side during dc-side faults. This dc fault

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aspect meanstransformer coupled H-bridges cannot be used. The ac gridcontribution to dc-side fault current is eliminated, reducing therisk of converter failure due to increased current stresses in theswitching devices during dc-side faults. From the grid standpoint,the dc fault reverse-blocking capability of the proposedHVDC system may improve ac network voltage stability, asthe reactive power demand at converter stations during dc-sidefaults is significantly reduced. The ac networks see the nodeswhere the converter stations are connected as open circuitnodes during the entire dc fault period. However, operation ofthe hybrid multilevel VSC requires a voltage-balancing schemethat ensures that the voltages across the H-bridge cells aremaintained at under all operating conditions, whereis the total dc link voltage. The H-bridge cells voltage balancingscheme is realized by rotating the H-bridge cell capacitors,taking into account the voltage magnitude of each cell capacitor and phase current polarity. An additional PI regulator is usedto ensure that the cell capacitors be maintained at asdepicted in Fig. 2(b) (inner control layer).

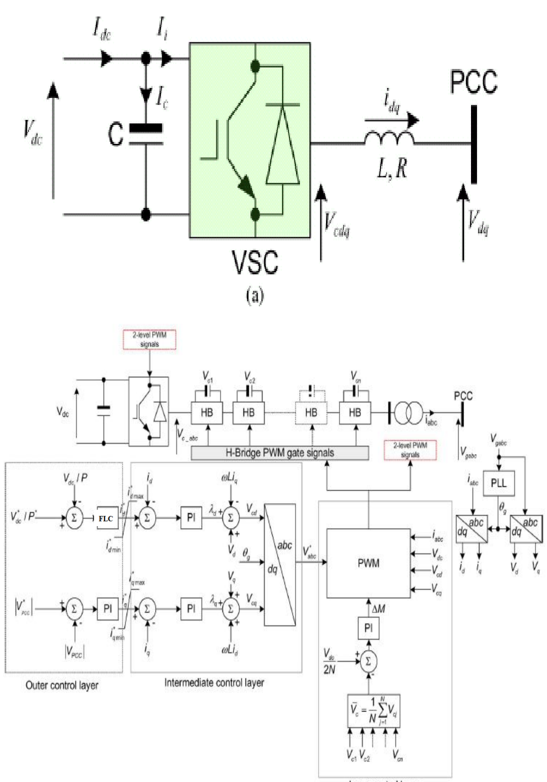

Fig. 2. (a) Representation of VSC station and (b) schematic diagram summarizing the control layer of the hybrid multilevel converter with ac side cascaded

III. CONTROL SYSTEMS

FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic. Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

Fuzzy Control Rule

e \ de	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NM	NM	NM	NS	Z	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PM	PM	PM	PL
PL	ZE	PS	PM	PL	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

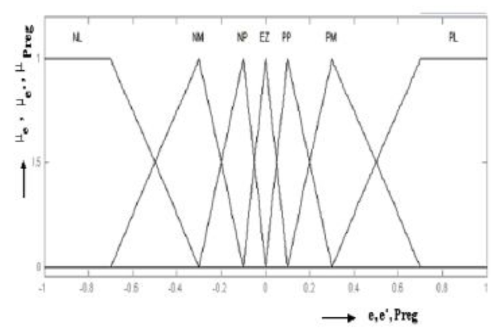

Fig. 4. Memberships function for the input and output variables.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL).A trend that is growing in visibility relates to the use of fuzzy logic in combination with neuron computing and genetic algorithms.

The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems whose MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.The fuzzy logic toolbox is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to methodology of fuzzy logic and its wide ranging applications.

TABLE I

CONVERTER STATIONS PARAMETERS

Converters 1 and 2	
Power ratings	687MVA
Maximum active power capability	600MW
Maximum reactive power capability	335MVAr
Two-level dc link voltage	600kV
H-bridge dc link voltage	42.86kV
Two-level dc link capacitance	150μF
H-bridge cell capacitance	3mF
H-bridge switching frequency	1kHz
Converter 1 controllers	
Current controller: K_p	35
Current controller: K_i	3000
Power controller: K_{pp}	0.0015
Power controller: K_{ip}	20
AC voltage controller: K_{pv}	30
AC voltage controller: K_{iv}	500
Converter 2 controllers	
Current controller: K_p	38
Current controller: K_i	2000
DC voltage controller: K_{pdc}	0.015
DC voltage controller: K_{idc}	0.0573
AC voltage controller: K_{pv}	0.00015
AC voltage controller: K_{iv}	400

TABLE II

CONVERTER TRANSFORMER PARAMETERS

Transformers 1 and 2	
Power rating	687MA
Voltage ratio	330kV/400kV
Per unit impedance	(0.0008+j0.32)

TABLE III

TRANSMISSION SYSTEMS PARAMETERS

Lines parameters (based on lumped π model)	
ac line length	60km
ac line series impedance	(0.0127+j0.2933)Ω/km
ac line shunt capacitance	12.74nF/km
dc transmission distance	75km
dc line series resistance	13.9mΩ/km
dc line series inductance	0.159mH/km
dc line shunt capacitance	0.231μF/km

Gains for all of the controllers and testnetworkparameters used in this paper are listed inTables I–III

IV. Performance Evaluation

The viability of the VSC-HVDC system that uses a hybridmultilevel VSC with ac-side cascaded H-bridge cells is investigatedhere, with emphasis on its dynamic performance during network alterations. In the steady state, the test network in Fig. 3(a) is used to assess its power control and voltage supportcapabilities. To further illustrate the advantages of multilevel converter during ac and dc network disturbances,the same test network is subjected to a three-phase ac-sidefault and a pole-to-pole dc-side fault at locations depicted inFig. 3(a), both for a 140-ms duration. Converter stations 1 and2 in Fig. 3(a) are represented by detailed hybrid VSC modelswith seven cells per phase, with the controllers in Fig. 2(b)incorporated.Seven cells per arm are used in this paper in orderto achieve acceptable simulation times without compromisingresult accuracy, as each system component is represented indetailed. Also, the hybrid converter with seven H-bridge cells
per phase generates 29 voltage levels per phase, which is thesame as the two-switch modular multilevel converter with 28cells per arm, for the same dc link voltage such that devicesin both converters experience the same voltage stresses. The converters are configured to regulate active power exchangeand dc link voltage, and ac voltage magnitudes at andrespectively. The test system in Fig. 3(a) is simulated inthe MATLAB Simulink environment.

A. Four-Quadrant Operation and Voltage Support

To demonstrate four0quadrant operation and voltage supportcapability of the presented VSC-HVDC system, converter station1 is commanded to increase its output power export fromgrid to from 0 to 0.5 pu (343.5 MW) at 2.5 pu/s. Attime 1 s it is commanded to reverse the active power flowin order to import 343.5 MW from grid , at 2.5 pu/s. At
a load of is introduced to , illustrating the voltage support capability of converter station 2during network alteration.
Fig. 3(b) and (c) show converters 1 and 2 active and reactivepower exchange with and respectively. Theconverters are able to adjust their reactive power exchange withand in order to support the voltage

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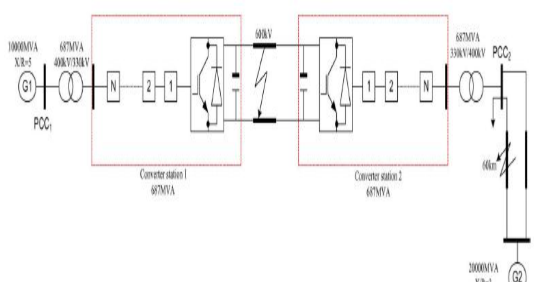
during the entire operating period. Fig. 3(c) and (d) show that converter2 adjusts its reactive power exchange with when theload is introduced at 2 s to support the voltage magnitude.Fig. 3(e) and (f) show that converter 2 injects and presentshigh-quality current and voltage waveforms into withno ac filters installed). Fig. 3(g) demonstrates that the voltagestresses across the H-bridge cell capacitors of converter 1 arecontrolled to the desired set point during the entire period.Fig. 3(h) displays the total dc link voltage across converter 2,which regulates the dc link voltage. Based on these results, theproposed VSC-HVDC system is able to meet basic steady-staterequirements, such as provision of voltage support and fourquadrant operation without compromising the voltage andcurrent stresses on the converters switches.

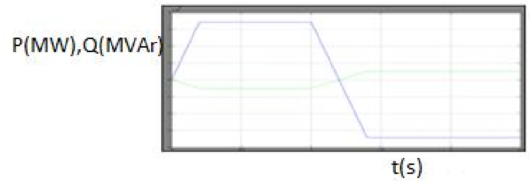
B. AC Network Faults

To demonstrate the ac fault ride-through capability of the presentedHVDC system, the test network is subjected to a 140 msthree-phase fault to ground at the location shown in Fig. 3(a).During the fault period the power command to converter 1 isreduced in proportion to the reduction in the ac voltage magnitude(this is achieved by sensing voltage). This is tominimize the two-level converter dc link voltage rise because ofthe trapped energy in the dc side, since power cannot be transferredas the voltage at collapses. Fig. 4 displays the resultswhen the test network exports 0.5 pu (343.5 MW) fromgrid to and is subjected to the three-phase fault at .Fig. 4(a) shows the active and reactive powers converter 1 exchangeswith. Note that converter 1 matches its activepower export to in order to minimize the rise of converter2 dc link voltage as its ability to inject active power into gridreduces with the voltage collapse at , as shown inFig. 4(d) and stated above. Fig. 4(b) shows the active and reactivepowers that converter 2 injects into. The systemis able to recover as soon as the fault is cleared, and converter

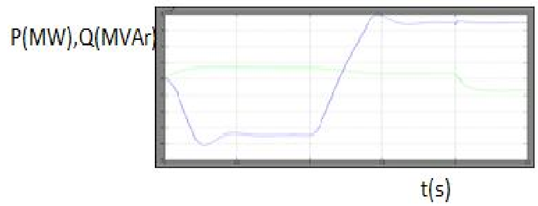


(a)

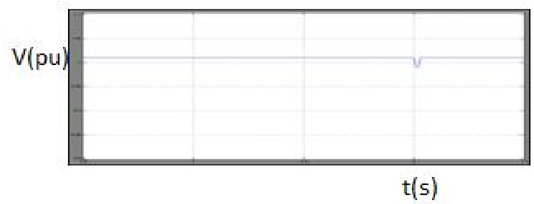
3(a)



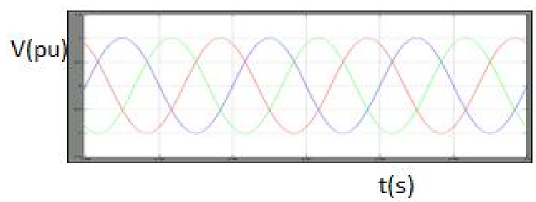
3(b)



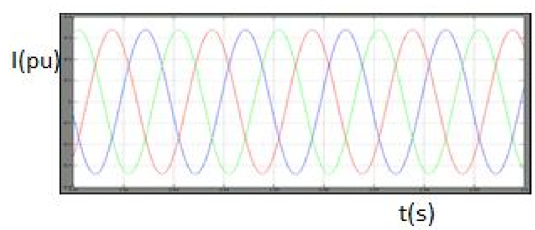
3(c)



3(d)

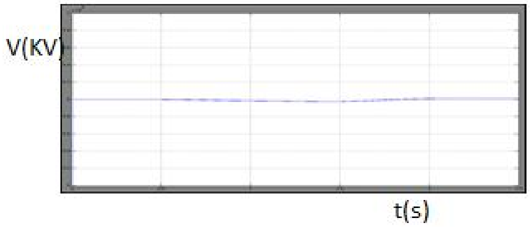


3(e)



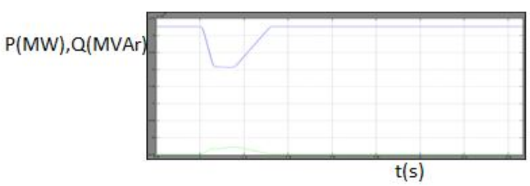
3(f)

3(g)

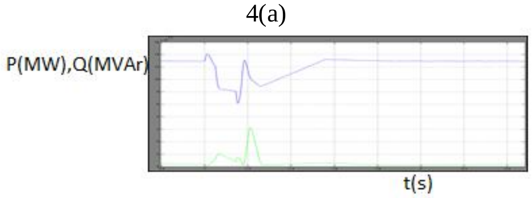


3(h)

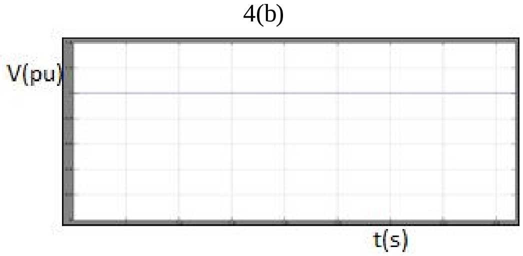
Fig. 3. Test network and waveforms demonstrating the steady-state operation of HVDC system based on hybrid voltage source multilevel converter with ac sidecascaded H-bridge cells. (a) Test network used to illustrate the viability of the hybrid multilevel voltage source converter HVDC systems; (b) active and reactivepower converter station 1 exchanges with pcc1; (c) active and reactive power converter station 2 exchanges with pcc2 ; (d) voltage magnitude at pcc2;(e) voltage waveforms at pcc2; (f) current waveforms converter station 1 exchanges withpcc1 ; (g) voltage across 21 cell capacitors of the three phases ofconverter 1; (h) voltage across the dc link of converter station 2 adjusts its reactive power exchange with grid in order support voltage at [see Fig. 4(d)]. The transients shown of active and reactive powers at PCC2 are related to the reaction of the ac voltage controller that regulates the ac voltage at . Fig. 4(c) shows that the voltage magnitude at remains unaffected; confirming that the hybrid voltage source



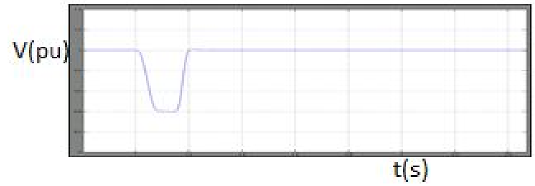
4(a)



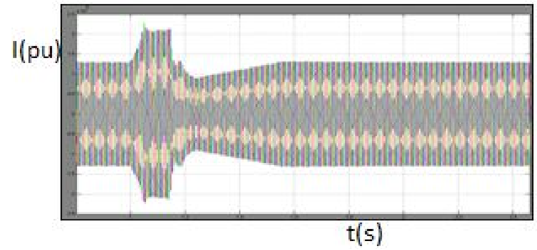
4(b)



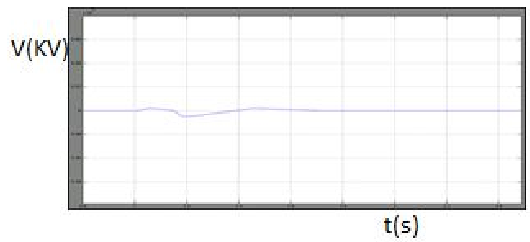
4(c)



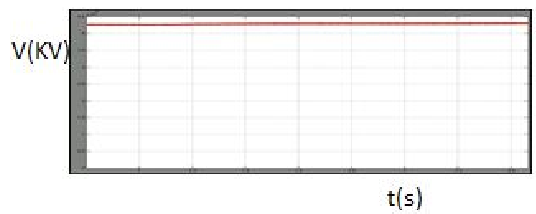
4(d)



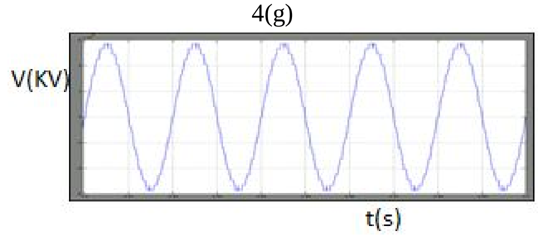
4(e)



4(f)



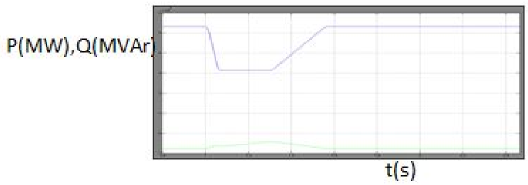
4(g)



4(h)

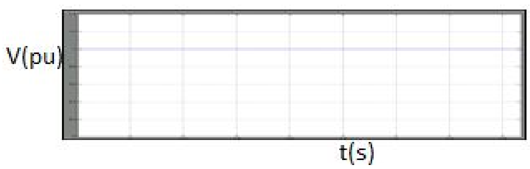
Fig.4. Waveforms demonstrating ac fault ride-through capability of HVDC transmission systems based on hybrid voltage multilevel converter with ac sidecascaded H-bridge cells. (a) Active and reactive power converter 1 exchanges with (b) Active and reactive power converter 2 injects into . (c)Voltage magnitude at (d) Voltage magnitude at (e) Current waveforms converter 2 injects into . (f) Converter 2 dc link voltage. (g) Voltageacross 21 H-bridge cells of the converter 2. (h) multilevel converter does not compromise the HVDC transmission system's decoupling feature despite adopting active power matching at converter 1, as explained. Fig. 4(e) shows that converter 2 restrains its contribution to the fault current to less than full load current despite

the voltage at collapsing to 20% of its rated voltage, due to converter 2's current controller. Fig. 4(f) shows that coordination of the HVDC controllers, as illustrated,minimizes the impact of ac-side faults on the transient



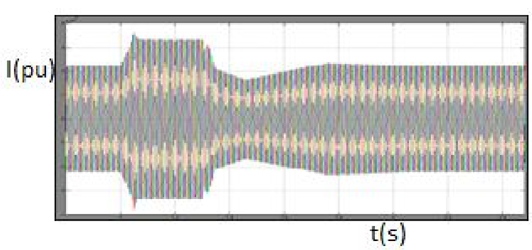
4(i)

4(j)

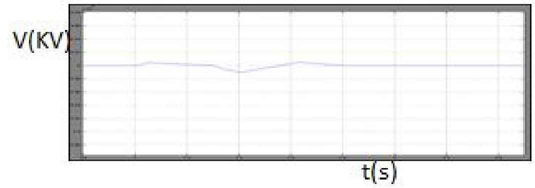


4(k)

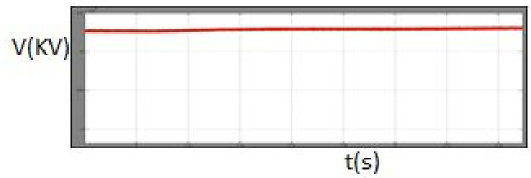
4(l)



4(m)

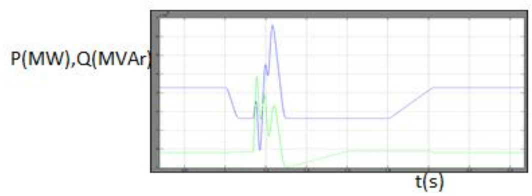


4(n)

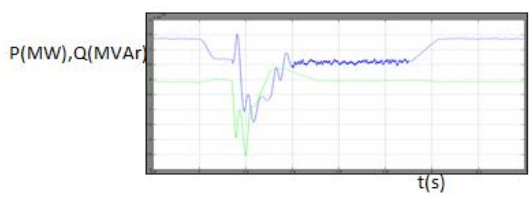


4(o)

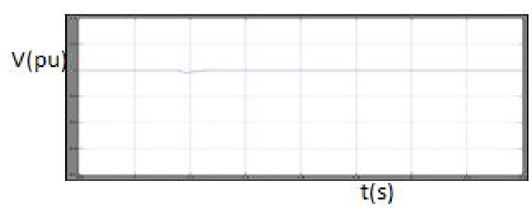
(i) Active and reactive power atPCC1. (j) Active and reactive power at PCC2. Results in (i)–(o) demonstrate the case when the converter stations operate close to their maximum active powercapabilities (power command at converter 1 is set to 0.75 pu, which is 515 MW) and system is subjected to a three-phase fault with a 300-ms duration.



5(a)



5(b)



5(c)

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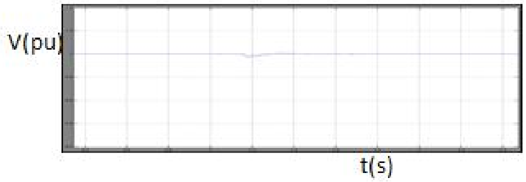
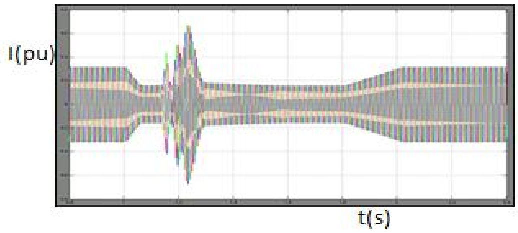
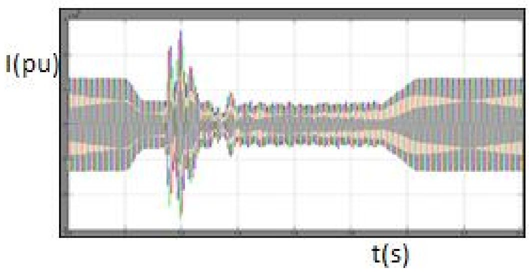


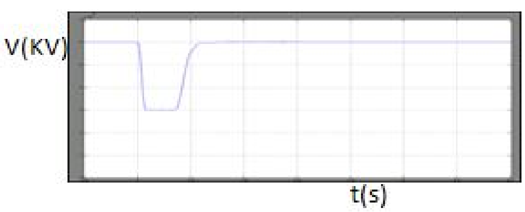
5(d)



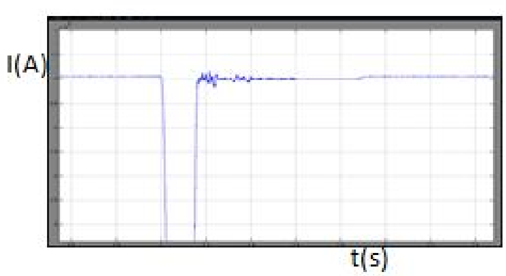
5(e)



5(f)

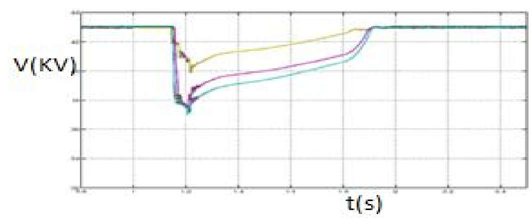


5(g)

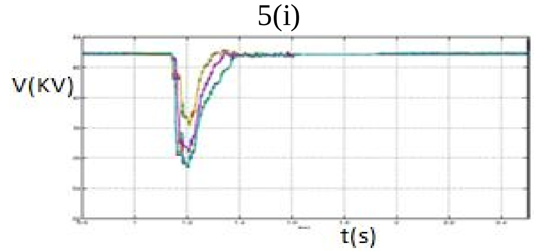


5(h)

Fig5. Waveforms demonstrating dc fault ride through capability of HVDC transmission systems based on hybrid voltage multilevel converter with ac sidecascaded H-bridge cells. (a) Active and reactive power converter 1 exchanges with (b) Active and reactive power converter 2 exchanges with .(c) Voltage magnitude at . (d) Voltage magnitude at (e) Current waveforms converter 1 exchange with grid at . (f) Current waveformsconverter 2 exchange with grid at(g) Converter 2 dc link voltage. (h) Zoomed version of dc link current demonstrating the benefits of dc fault reverseblocking capability.Charge from both ac sides; this causes a large current flow from both ac sides to the dc side to charge the dc link capacitors and cable distributed capacitors as shown in Fig. 5(e) and 5(f). The results in Fig. 5(e) and 5(f) also demonstrate the benefits of dc fault reverse blocking capability inherent in this hybrid system, as the converter switches experience high current stresses only during dc link voltage build-up. Fig. 5(g) shows that converter 2 dc link voltage recovers to the pre-fault state after the fault



5(i)



5(j)

Fig. 5.(*Continued*.) Waveforms demonstrating dc fault ride-through capability of HVDC transmission systems based on hybrid voltage multilevel converter withac side cascaded H-bridge cells. (i) Voltage across the H-bridge cell capacitors of converter 1. (j) Voltage across the H-bridge cell capacitors of converter 2 is cleared. Notice the recovery period for the dc link voltage isrelatively long; this is the major disadvantage of the proposedHVDC systems as it uses a common dc link capacitor. Fig. 5(h)expands the dc fault current and shows the 60-kA peak decaysto zero in less than four cycles (for 50 Hz) after discharge of dclink and cable distributed capacitors. This result confirms thepossibility of eliminating dc circuit breakers to isolate permanentdc side faults in dc networks that use HVDC converterswith current limiting capability. Fig. 5(h) also shows the acgrids start to

contribute to the dc link current after the fault iscleared, to charge the dc side capacitors. Fig. 5(i) and (j) showsthe voltage across the 21 H-bridge cells of the converter stations1 and 2 (each group of traces represent voltages across 7H-bridge cell capacitors in each phase). The voltage across theH-bridge cell capacitors remains unaffected during the entirefault period as the converters are blocked. The cell capacitorsstart to contribute energy to the main dc link capacitors duringdc link voltage build-up after restoration of the converter gatingsignals. This contribution creates a noticeable reduction in thecell capacitor voltages during system restart. The cell capacitorsof converter 2 that regulate dc link voltage, experience a largervoltage dip than converter 1, which regulates active power. However, the reduction in H-bridge cell capacitor voltages isminimized if large capacitance is used.

V. CONCLUSION

This paper presented a new generation VSC-HVDC transmissionsystem based on a hybrid multilevel converter with ac-sidecascaded H-bridge cells. The main advantages of the proposedHVDC system **state**Fuzzy Logic Control and network alterations, including its response to ac and dc side faults**.**are:

- potential small footprint and lower semiconductor lossescompared to present HVDC systems.
- low filtering requirements on the ac sides and presentshigh-quality voltage to the converter transformer.
- does not compromise the advantages of VSC-HVDC systemssuch as four-quadrant operation; voltage support capability;and black-start capability, which is vital for connectionof weak ac networks with no generation and windfarms.
- Modular design and converter fault management (inclusionof redundant cells in each phase may allow the system tooperate normally during failure of a few H-bridge cells; hence a cell bypass mechanism is required).
- Resilient to ac side faults (symmetrical and asymmetrical).
- inherent dc fault reverse blocking capability that allowsconverter stations to block the power paths between the acand dc sides during dc side faults (active power betweenac and dc sides, and reactive power exchange between aconverter station and ac networks), hence eliminating anygrid contribution to the dc fault current.

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