Research Journal of Applied Sciences, Engineering and Technology 5(24): 5534-5541, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: September 24, 2012 Accepted: October 09, 2012 Published: May 30, 2013

Integration of CCC-HVDC and VSC-HVDC Systems to Supply an Island Network

Ali BidadfarMehrdad, AbediMehdi Karrari and G.B. Gharehpetian
Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

Abstract: Acombination of Capacitor Commutated Converter (CCC) HVDC and voltage source converter (VSC) HVDC is proposed to supply an island system without any local generation. The key point of this integration is the flat characteristic of dc voltage of CCC-HVDC, which provides the condition for VSC to connect to CCC dc link via a current regulator. The advantages of proposed combined in feeding system are requiring only one dc line and having better dynamic responses. The structure of the proposed in feeding system as well as its control system is shown in this study. The simulation results are presented to confirm the effectiveness of the proposed system. Two other schemes for in feeding the passive island systems are studied to demonstrate the advantages of the proposed system.

Keywords: Capacitor Commutated Converter (CCC), HVDC, passive network, voltage source converter

INTRODUCTION

To supply the entirely passive ac networks or island systems without local generation, using the HVDC power transmission systems is a subject of great interest. Since the passive island network is a weak system and HVDC converters require relative strength to work properly, some methods must be used to provide the relative strength to such networks. Beside ac voltage support, supplying methods provide the reactive power of HVDC converters. These methods are introduced by Thio and Davies (1991), Nayak *et al.* (1994), DeOliveira *et al.* (1994), Zhuang *et al.* (1996) and ersen and Lie (2004) and Guo and Zhao (2010). The traditional devices to meet the requirements of HVDC converters to connect to the passive networks, have used to be the synchronous condensers (SCs). Nayak *et al.* (1994) and Zhuang *et al.* (1996) have studied the static compensators to provide the reactive power for the line-commutated converters (LCC) HVDC. DeOliveira *et al.* (1994) has studied the static VAR compensator (STATCOM) along with HVDC converter to supply an entirely passive ac system. Andersen and Lie (2004) has proposed simultaneous application of STATCOM and CCC-HVDC to supply a passive ac network. Guo and Zhao (2010) has introduced a double-infeed system consisting of LCC-HVDC and VSC-HVDC to supply a passive ac network.

The VSC-HVDC can supply the passive ac networks without local generation (Zhang *et al*., 2001; Sao and Lehn, 2006; Du *et al*., 2007; Zhao *et al*., 2008; Li *et al*., 2009). The VSC-HVDC uses pulse-width modulation (PWM) technique to generate the ac voltage with desired amplitude and phase angle, (Ding *et al*., 2008). However, Zhang *et al.* (2011) investigated the problems in VSC-HVDC control process when it is connected to a weak power system.

This study proposes the combination of CCC-HVDC and VSC-HVDC to supply a passive ac network. The schematic diagram of this combination is shown in Fig. 1. This structure benefits from two advantages; it has only one dc line and consequently one dc supply; also, the VSC can participate in active power transfer, which can be used for stability improvement in transient conditions.

PROPOSED INFEEDING SYSTEM

The structure of the proposed infeeding system for an entirely passive ac network is demonstrated in Fig. 1. The VSC generates the balanced three-phase ac voltages and supplies the determined amount of active power as well as the required reactive power of CCC. These functions are being done by VSC in steady state, when CCC is supplying a main value of network active power. In transient conditions, the VSC manipulates the active power between dc line and ac network to damp the oscillations quickly and keeps the ac voltage almost constant. The active power manipulation is carried out through a current regulator, which is a gate turn-off (GTO) thyristor series with a small inductor. The current regulator is the unidirectional path, which sends the energy from receiving end of dc line to dc bus of VSC.

Corresponding Author: Ali Bidadfar Mehrdad, Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

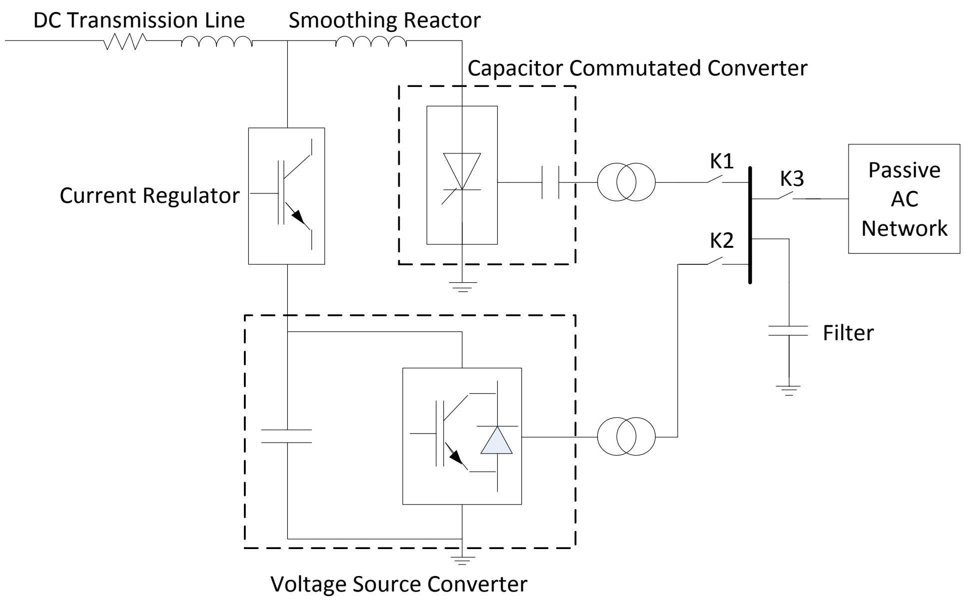

Fig. 1: Combination of CCC-HVDC and VSC-HVDC

In black-start time, the current regulator establishes the dc voltage of the VSC. The VSC, in turn, generates the three-phase voltages with desired amplitude and frequency, while the switch K2is closed and K1 and K3 are open (Fig. 1). In second step, switch K1 is closed and CCC gets ready to supply the power. At last, switch K3supplies the ac voltage to the network.

PRINCIPLES OF PROPOSED INTEGRATION

The power transfer principal of LCC is different from that of VSC. In LCC, the power transition is adjusted by changing the dc voltage level, while the dc current is kept almost constant. However, in VSC, the transmitting power is adjusted by dc current, while its dc voltage is kept almost constant. Consequently, the dc terminals of both converters are inherently different and their direct connection to each other is basically impossible.

When LCC is connected to a weak ac system, it suffers from valves commutation failures. This drawback is generally compensated by commutation capacitors application in series with valves and subsequently, the CCC is developed (Reeve *et al*., 1968; Kazachkov and Schenectady, 1998).These capacitors offer additional voltages for valves allowing the use of smaller firing angles and extinction angles in the rectifier and inverter, respectively.

One of the main advantages of CCC over LCC, is the flatness of its dc voltage-current characteristic, which has been presented by Reeve *et al.* (1968), Kazachkov and Schenectady (1998) and Sadek *et al*. (1998). This characteristic is illustrated in Fig. 2. The

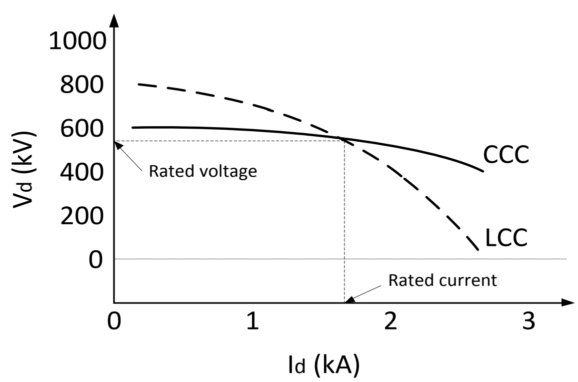

Fig. 2: DC voltage-current charectristics of LCC and CCC

flatness of dc voltage of CCC is the key point to propose the combination of CCC and VSC. In fact, the dc bus of VSC is connected to the point between the dc line and smoothing reactor of CCC. The connection between two converters is done via a GTO switch series with a small inductor, as shown in Fig. 3.

The inductor in current regulator avoids the sudden inrush current when GTO starts conducting at instant when there exist two different voltage levels at its both sides. However, this inductance is not too large to cause an unbearable overvoltage across the VSC capacitor.

Connecting the current regulator to the point where the dc line and smoothing reactor have been tied, the current flowing toward the VSC will not significantly disturb the CCC dc current. Thus, the normal operation of CCC will not be affected by the existence of current regulator.

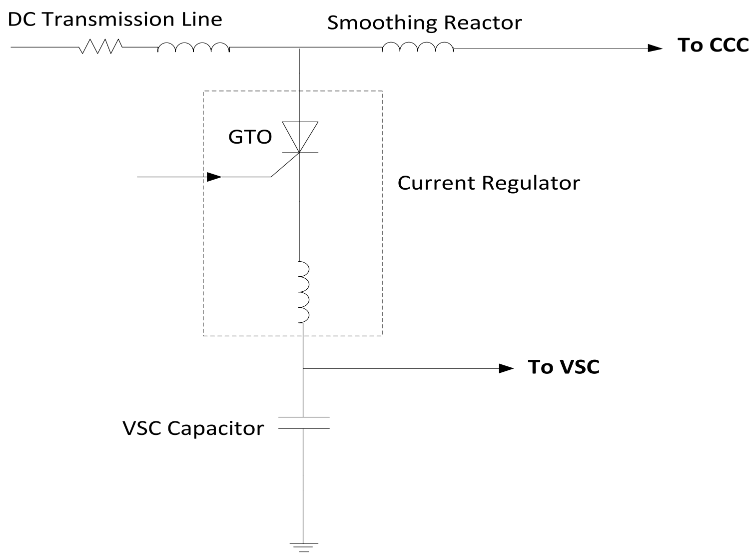

Fig. 3: Current regulator connection

CONTROL SYSTEM

The main task of the control system is to provide an almost stiff control to both converters, so that an ac voltage with desired amplitude and frequency is being established on a passive network.

It is assumed that the converter in rectifier station is operating in constant dc voltage mode so that the converters at the inverter station can control network active power. In this study the operation of rectifier station is not interested and only the constant dc voltage is representing this station. In steady state operation, the most percentage of the network active power is delivered by CCC and the network ac voltage amplitude as well as its frequency is controlled by VSC. However, in transients, the VSC participates more in active power transfer so that the fast damping of oscillations occurs.

VSC control: The VSC composed of a three-phase PWM converter which generates the voltage vector v in its output and a transformer which connects the converter to the filter bus with voltage vector u_f. The converter is controlled by vector current control, which uses *dq* decoupling technique (Kazmierkowski and Malesani, 1998; Choi and Sul, 1998; Kazmierkowski *et al*., 2002). The basic principle of this control strategy is to control the active power and the reactive power independently through an inner-current control loop. A simple implementation of a current controller is achieved by the proportional-type control law as following:

$$v^c_{ref} = \alpha_c L_c \left(i_{ref} - i^c_c\right) + j\omega L_c i^c_c + H_{LP}(s) u^c_f \quad (1)$$

where,

α_c = The desired closed-loop bandwidth of the inner-current controller
i_{ref} = The converter current reference
$v^c{}_{ref}$ = The voltage reference of the VSC
ω = The network angular frequency

The superscript c denotes the converter *dq* frame. The term $j\omega L_c\, i^c{}_c$ is used to remove the so-called cross-coupling (Zhang, 2010). The function H_{LP} (s) is a low-pass filter to improve the disturbance rejection capability of the current controller. H_{LP} (s) has the following expression:

$$H_{LP}(s) = \frac{\alpha_f}{s + \alpha_f} \quad (2)$$

where, α_f is typically chosen with a bandwidth (40 −100 rad/s), (Harnefors *et al*., 2007). The direct and quadrature components of i_{ref} are obtained from active power controller (APC) and alternating-voltage controller (AVC), respectively. These two controllers are simply the PI-controller types, which have been presented by (3) and (4):

$$i^d_{ref} = \left(K^P_p + \frac{K^P_i}{s}\right)\left[P^{vsc}_{ref} - P^{vsc}\right] \quad (3)$$

$$i^q_{ref} = \left(K^U_p + \frac{K^U_i}{s}\right)\left[U_{ref} - U_f\right] \quad (4)$$

In vector current control, the *dq* components of converter current always follow the corresponding current references. Consequently, by limiting the modulus of the current references, the valve current of

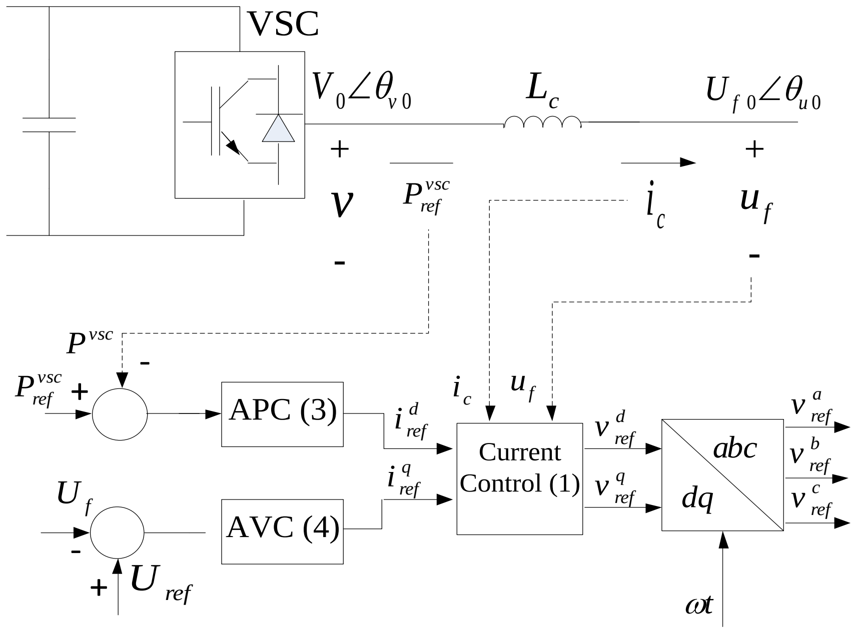

Fig. 4: Main circuit and control block diagram of VSC using current vector control

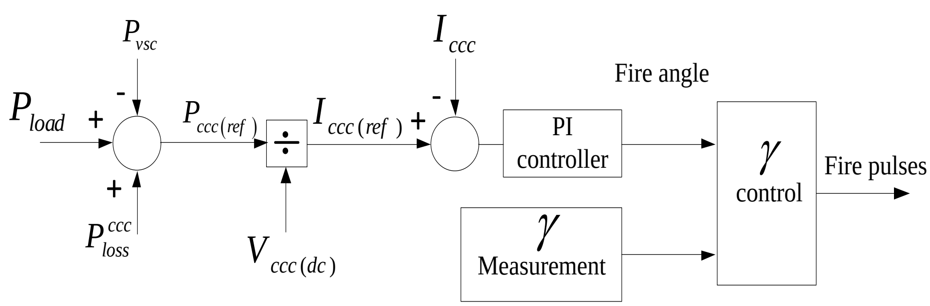

Fig. 5: Control block diagram of CCC

the converter is limited in fault condition. The main circuit and control block diagram of the VSC are shown in Fig. 4, in which L_c is the leakage inductance of connecting transformer. The output of the control block diagram is the three-phase ac reference signal which is fed to PWM section to generate the firing pulses for VSC switches.

CCC control: The CCC control is based on delivering the most percentage of network active power. However, by proposed structure of in feeding system, the VSC can participate in active power transmission either. The CCC control block diagram is presented in Fig. 5.

where,

P_{load} = The network total active power
P_{vsc} = The VSC active power
$P^{ccc}{}_{ref}$ = The reference value of CCC active power
$P^{ccc}{}_{loss}$ = The power losses through the CCC and smoothing reactor
$V^{ccc}{}_{dc}$ = The receiving end voltage of dc line
$I^{ccc}{}_{ref}$ = The reference value of the dc current flowing through the CCC
$I^{ccc}{}_{ref}$ = Compared with its corresponding measured value
I_{ccc} = The resultant is given to PI-controller to generate the CCC valves firing pulses

On the other hand, the extinction angle, γ is measured to ensure that the fire angle in not too large to cause the commutation failure in converter.

VSC dc-voltage control: As it was mentioned earlier, the VSC dc voltage is energized by dc line voltage through the current regulator. When the measured value of VSC dc voltage is lower than its reference value, the current will be conducted from dc line to VSC dc capacitor. On the other hand, a predetermined amount of VSC active power, $P^{vsc}{}_{ref}$, will not allow the VSC dc capacitor to be overcharged.

SIMULATION STUDIES

To validate the proposed structure of passive network in feeding system, simulation studies are carried out for different conditions. The passive network is a 230 kV, 50 Hz system with 410 MW passive load and 100 MW motor-load. As it was mentioned earlier, the dc line voltage is controlled by rectifier station, which is not considered in the studies. The dc line is modeled with 0.2 Ohm resistance in series with inductance of 0.1 H. The CCC series capacitor is of 0.3mF capacitance and VSC capacitor is 0.2 mF. The smoothing reactor of CCC has 0.5 H and current regulator has 0.0001 H inductance. The CCC transformer has 1000 MVA power capacity with 0.15 pu leakage inductance and the VSC transformer has 500 MVA power and 0.1pu leakage inductance. Both transformers possess 0.04 pu copper losses. The capacitive filter in ac network has 35 MVAR reactive power. $K^{p}{}_{p}$ and $K^{p}{}_{i}$ are equal to 20 and 100 rad/s, respectively. $K^{U}{}_{p}$ and $K^{U}{}_{i}$ are set to10 and 80 rad/s. In addition, the CCC PI-controller gains are 10 and 100 rad/s. Three different simulations are carried out as follow:

Network load changing: In this simulation, two scenarios are regarded: the first one, at 6.0 s, a45 MW motor load is added to the network; in the second one, 50 MW active power is shifted from CCC to VSC at 8.0 s. Fig. 6 to 10 are showing the responses to these changes. As it is shown in Fig. 6, after motor load connection, the VSC takes that incoming load instantly, because the VSC is faster than CCC. In addition, when the 50 MW power is transferred from CCC to VSC, there are no significant oscillations in load active power. This is because the amplitude and frequency of ac voltage have not been considerably affected. Fig. 7 proves the stiffness of the voltage amplitude. As shown in Fig. 8, the VSC dc voltage is adjusted to 190 kV. However, the new added load is not supposed to be supplied by VSC, thus it is transferred from VSC to CCC by adjusting the CCC firing angle that is shown in Fig. 9.

The induction motor speed, the one was connected earlier, is shown in Fig. 10, which demonstrate the entrance of new load and power shifting between converters have no substantial effect on induction motor speed.

The reduction of DCvoltage: Another scenario is considered as a reduction of dc line voltage. In this

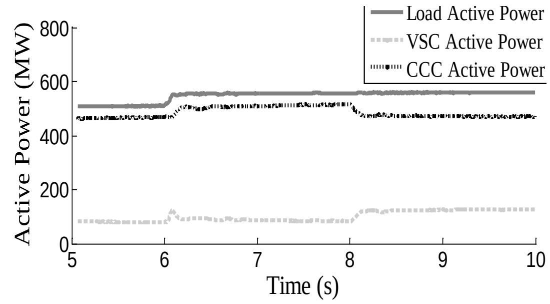

Fig. 6: Active power of load, CCC and VSC

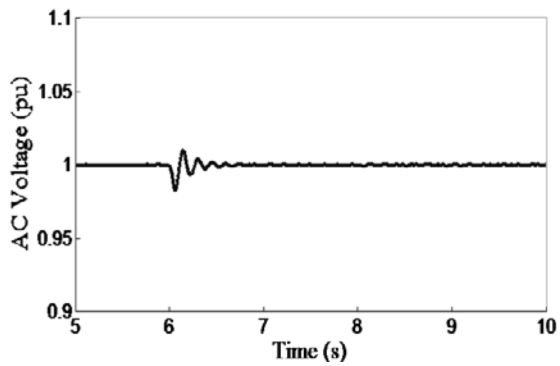

Fig. 7: Ac voltage (pu) of the network

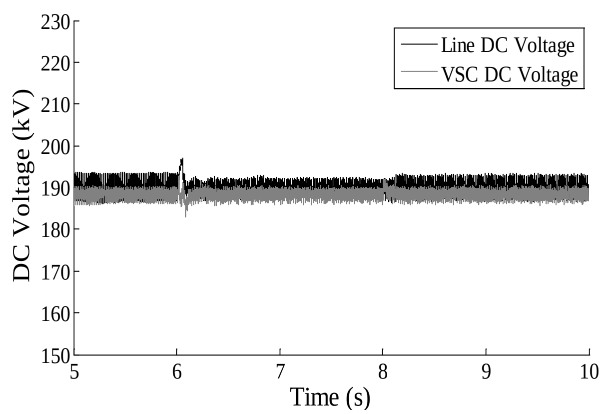

Fig. 8: Voltages of dc line and VSC dc link

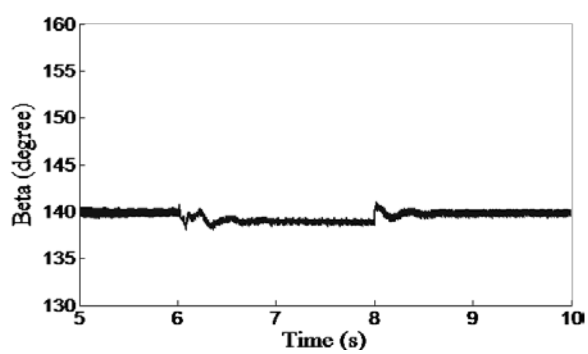

Fig. 9: CCC firing angle

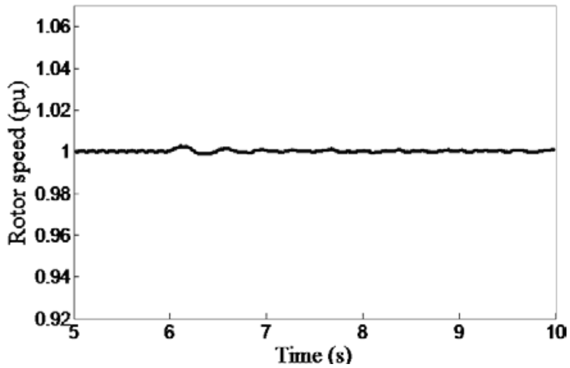

Fig. 10: Rotor speed of induction motor

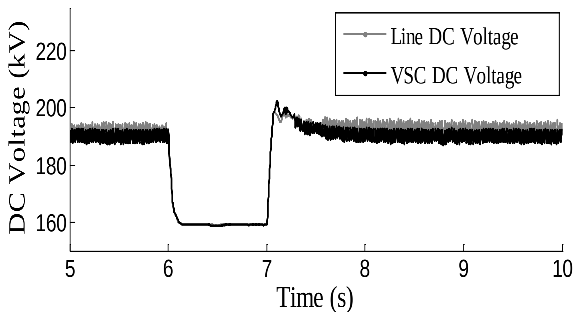

Fig. 11: Voltages of dc line and VSC dc link when voltage of dc line drops by 20%

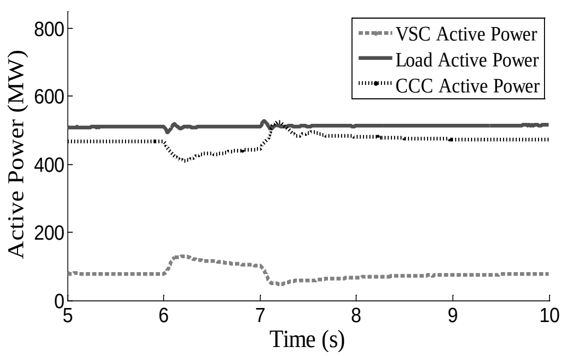

Fig. 12: Active power of load, CCC and VSC when dc line voltage drops by 20%

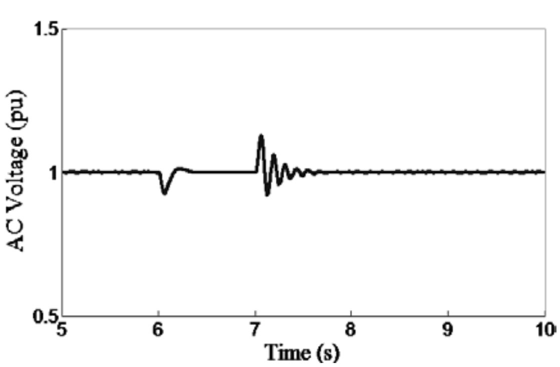

Fig. 13: Ac voltage of the network when voltage of dc line drops by 20%

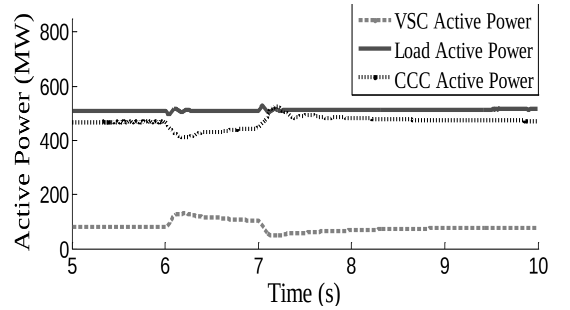

Fig. 14: Active power of load, CCC and VSC under dc voltage reduction when two separate dc lines are used

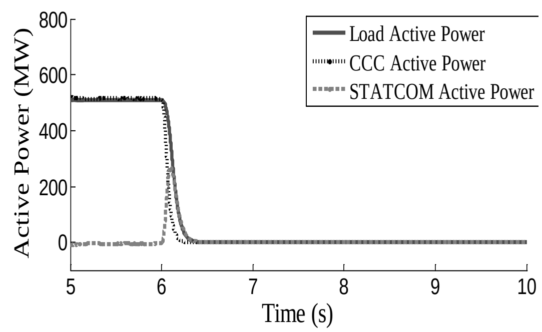

Fig. 15: Active power of load, CCC and STATCOM under dc voltage reduction when the capacitance of STATCOM dc link is 0.2 mH

case, the supplying dc voltage drops 20% lower than its nominal value, as shown in Fig. 11 to 13.When the voltage reduction occurs, the deviation of the load active power is not substantial in comparison with those of CCC and VSC active powers, as shown in Fig. 12. The active power of CCC is reduced because of dc voltage fall; on the other hand, the active power of VSC is increased immediately to compensate the CCC power lessening.

To make more comparisons, two other schemes of infeeding systems are studied herein. As it is mentioned before, Guo and Zhao (2010) has studied an infeeding system composed of LCC-HVDC and VSC-HVDC with two separate dc lines, known as double infeed system. Here for this system is used to make comparison with proposed structure. However, in double infeed system CCC is used instead of LCC in this study. The same scenario, CCC dc voltage fall by 20%, is considered when CCC and VSC with two separate dc lines are composing the infeeding system. For this system, the active power curves of CCC, VSC and load are shown in Fig. 14.

The curves in Fig. 12 and 14 are almost the same; however, the power variations in Fig. 14 are lower than that of Fig. 12. This is because when two separate dc lines are used, the VSC dc voltage is not directly subjected to the sudden reduction of CCC dc voltage.

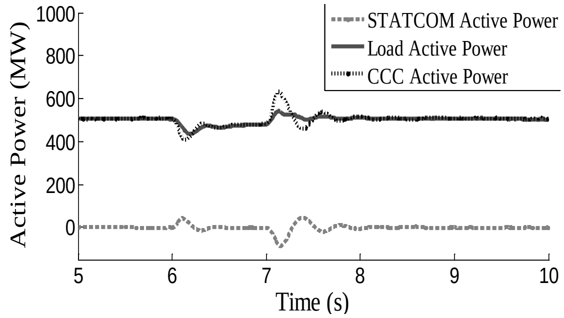

Fig. 16: Active power of load, CCC and STATCOM under dc voltage reduction when the capacitance of STATCOM dc link is 2.0 mH

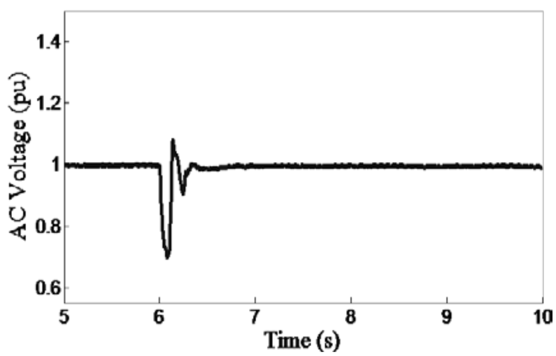

Fig. 17: AC Voltage in per-unit under the short circuit fault

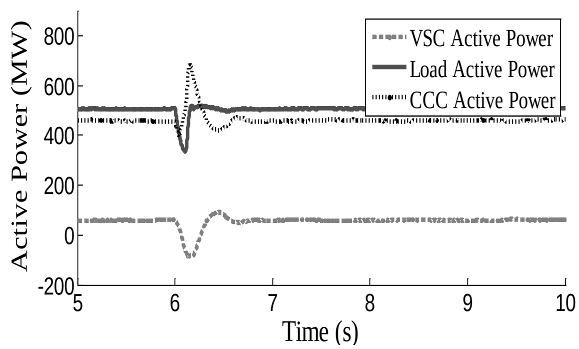

Fig. 18: Active power of load, CCC and VSC under single-phase short circuit fault when one dc line is used for both converters

Nevertheless, the scheme proposed in this study benefits from having only one dc line.

Another simulation is carried out for infeeding system made of CCC-HVDC and STATCOM, which has been introduced by Andersen and Lie (2004). In that system, the CCC operates with constant power and the STATCOM is controlled by the strategy given by Andersen and Lie (2004). The STATCOM with 0.2 mF capacitance in its dc bus cannot support the network ac voltage; therefore, the infeeding system fails, as shown in Fig. 15.The STATCOM capacitor is increased to 2.0 mF in this study to improve the in feeding system

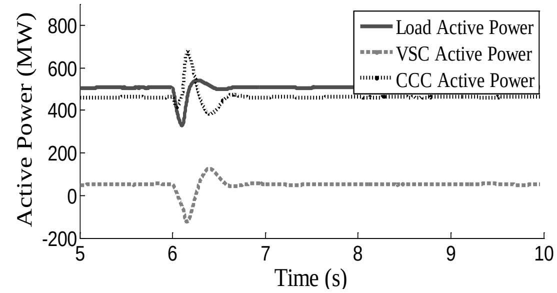

Fig. 19: Active power of load, CCC and VSC under single-phase short circuit fault when two separate dc lines are used for converters

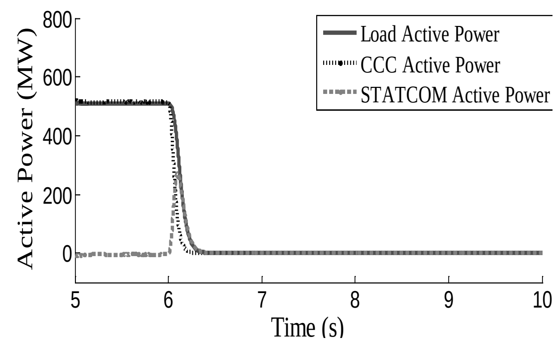

Fig. 20: Active power of load, CCC and STATCOM under single-phase short circuit fault

stability. Also, it is clear from Fig. 16 that the load and CCC power have been reduced during the fault. This is because the CCC is working with maximum firing angle and consequently with its maximum current so that the power reduction cannot be compensated more.

Shot circuit fault occurance: A single-phase short circuit is occurred in ac side where two converters have been connected to the loads. The fault is occurred at 6.0 s and is cleared at 0.7 s; as shown in Fig. 17. To compare the proposed infeeding system with other two aforementioned systems under the same fault condition, the results are presented in Fig. 18 to 20. As it is shown in curves, there is no major difference between the responses of the proposed system with those of double infeed system. Nevertheless, when CCC and STATCOM are supplying the passive network, the oscillations in active powers are significant.

CONCLUSION

In this study, the new passive network infeeding system composed of CCC and VSC-HVDC has been proposed. It has been shown that the VSC can participate in active power transition and share the infeeding load to the network. The simulation results have been presented for different scenarios to confirm the effectiveness of the proposed infeeding system. Also, it has been shown that the proposed system has almost the same performance as the system composed of CCC and VSC with two separate dc lines; nevertheless, the proposed system benefits from having only one dc line. In comparison with the infeeding system made of CCC and STATCOM, the proposed system has revealed more safety and ability of supplying the load power.

REFERENCES

Andersen, B.R. and X. Lie, 2004. Hybrid HVDC system for power transmission to island networks. IEEE T. Power Deliver., 19(4): 1884-1890.

Choi, J.W. and S.K. Sul, 1998. Fast current controller in three-phase AC/DC boost converter using d-q axis crosscoupling. IEEE T. Power Electr., 13(1): 179-185.

DeOliveira, M., M. Poloujadoff, A. LeDu and P.G. Therond, 1994. Supply of an entirely passive AC system through an HVDC link. J. Elect. Power Energy Syst., 16(2): 111-116.

Ding, G., M. Ding and G. Tang, 2008. An innovative hybrid PWM technology for VSC in application of VSC-HVDC transmission system. Proceeding of Electric Power Conference, Canada, pp: 1-8.

Du, C., M.H.J. Bollen, E. Agneholm and A. Sannino, 2007. A new control strategy of a VSC-HVDC system for high-quality supply of industrial plants. IEEE T. Power Deliver., 22(4): 2386-2394.

Guo, C. and C. Zhao, 2010. Supply of an entirely passive AC network through a duble-infeed HVDC system. IEEE T. Power Electr., 24(11): 2835-2541.

Harnefors, L., M. Bongiornos and S. Lundberg, 2007. Input-admittance calculation and shaping for controlled voltage-source converters. IEEE T. Ind. Electron., 54(6): 3323-3334.

Kazachkov, Y. and N.Y. Schenectady, 1998. Fundamentals of a series capacitor commutated HVDC terminal. IEEE T. Power Deliver., 13: 1157-1161.

Kazmierkowski, M.P. and L. Malesani, 1998. Current control techniques for three-phase voltage-source PWM converters: A survey. IEEE T. Ind. Electron., 45(5): 691-703.

Kazmierkowski, M.P., R. Krishnan and F. Blaabjerg, 2002. Control in Power Electronics. Academic Press.

Li, S., M. Zhou, Z. Liu, J. Zhang and Y. Li, 2009. A study on VSC-HVDC based black start compared with traditional black start. Proceeding of International Conference on Sustainable Power Generation Supply, Nanjing, pp: 1-6.

Nayak, O.B., A.M. Gole, D.G. Chapman and J.B. Davies, 1994. Dynamic performance of static and synchronous compensators at an HVDC inverter bus in a very weak ac system. IEEE T. Power Syst., 9(3): 1350-1358.

Reeve, J., J.A. Baron and G.A. Hanley, 1968. A technical assessment of artificial commutation of HVDC converters with series capacitors. IEEE T. Power Ap. Syst., PAS-87(10): 1830-1840.

Sadek, K., M. Pereira, D.P. Brandt, A.M. Gole and A. Daneshpooy, 1998. Capacitor commutated converter circuit configurations for Dc transmissions. IEEE T. Power Deliver., 13(4): 1257-1264.

Sao, C. K. Sao and P.W. Lehn, 2006. Intentional islanded operation of converter fed microgrids. Proceeding of IEEE Power Engineering Society General Meeting, Min-neapolis, MN.

Thio, C.V. and J.B. Davies, 1991. New synchronous compensators for the Nelson river HVDC system-planning requirements and specifications. IEEE T. Power Deliver., 6(2): 922-928.

Zhang, L., 2010. Modeling and control of VSC-HVDC Links connected to weak AC systems. Ph.D. Thesis, Royal Institute of Technology, Stockholm, Sweden.

Zhang, G., Z. Xu and H. Liu, 2001. Supply passive networks with VSC-HVDC. Proceeding of IEEE PES Summer Meeting, Vancouver, BC, Canada.

Zhang, L., L. Harnefors and H.P. Nee, 2011. Modeling and control of VSC-HVDC links connected to island systems. IEEE T. Power Syst., 26(2): 783-789.

Zhao, C., L. Li, G. Li and C. Guo, 2008. A novel coordinated control strategy for improving the stability of frequency and voltage based on VSC-HVDC. Proceediong 3rd International Conference Electric Utility Deregulation Restructuring Power Technology, Nanjuing, pp: 2202-2206.

Zhuang, Y., R.W. Menzies, O.B. Nayak and H.M. Turanli, 1996. Dynamic performance of a STATCOM at an HVDC inverter feeding a very weak ac system. IEEE T. Power Deliver., 11(2): 958-964.