Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Analysis of Innovative HVDC Control

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***Abstract* -- HVDC control has much faster inherent capability of the response than the dynamic response of the AC system. The valve firing angle control has a transient response time of only few milliseconds with the accuracy of a fraction of an electrical degree for firing the converter valves. Consequently, the control can have a significant influence on the improvements of system stability e.g. fast power recovery after faults and quick response against the disturbances around the operating points. This paper introduces a new practical control concept to increase the performance of HVDC transmission. The studies are performed by the use of a back-to-back HVDC to compare the benefits of the new control concept with the conventional one during fault recovery. Furthermore, the comparisons of AC voltage transients between the use of the new and conventional control concept are investigated when fixed capacitor (FC) and fixed reactor (FR) are switched.**

***Index Terms* -- HVDC, advanced HVDC control, system performance**

I. Introduction

OVER last decade, the developments in the world's power demand have been rapidly grown. The future system development will move in the direction of the further interconnections, the transport of the large power blocks from the remote locations by the HVDC to the load centers [1]. The interconnected systems therefore are becoming extremely large with the diminution of the power supply reliability which can be observed from a number of large blackouts in Europe and America [2]. The interconnections of AC systems become partly weak and very weak which reduce the system stability. Consequently, the innovative solutions will be necessary to avoid the congestion and improve the system stability. Improving can be made by the use of the HVDC. Not only becoming the valuable alternative for long distance transmission, the HVDC has also the advantage of fast response for the urgent demand of power change. The HVDC can quickly clear the disturbances; therefore there is no negative effect to the blackouts in interconnected systems. Accordingly, an effective control of the HVDC system becomes an important role in improving system performance and stability.

The widely used conventional control concept termed **M**arginal **C**urrent **C**ontrol **M**ethod (MCCM) is the accepted concept used at present. It has been applied since 1954. The conventional HVDC control uses power control at the rectifier where the hierarchical power control supplies the DC current reference value (I_{dref}) for the subordinate DC **C**urrent **C**ontrol (CC). The inverter usually comprises the DC **V**oltage **C**ontrol (VC), the DC **C**urrent **E**rror **C**ontrol (CEC), the DC **C**urrent **C**ontrol (CC) and the **C**onstant **E**xtinction **A**ngle control (CEA); however these inverter controls are not activated simultaneously. It can be seen that the inverter consists of a number of control modes, the mode shift can therefore occur during the disturbances. This mode shift is disruptive and can in certain cases harm AC system operation. Moreover, the current margin has to be considered in the MCCM [3]. If this margin becomes too large, the occurred mode shift will cause a severe effect to the systems. On the other hand if this current margin becomes small, the current harmonic can provoke the mode chatter where the rectifier and the inverter continuously shift current control back and forth. These drawbacks will not occur in the new control concept termed **C**ombined and **C**oordinated **C**ontrol **M**ethod (**CCCM**).

The CCCM was firstly introduced in 1996 [3] , however, till now this method was not implemented in the realized projects. Using this method the rectifier controls power directly (not through the current control) and the equivalent resistance ("U_d/I_d") control is functioned at the inverter. The transmitted power is therefore controlled directly without the delay. Consequently, the control can carry out its function against the disturbances faster than the conventional MCCM. Obviously, as the inverter comprises only the equivalent resistance control, the mode shift can therefore not occur during disturbances.

This paper will start with the basic concept of the MCCM in comparison with the CCCM when the AC voltages drop at either rectifier or inverter. Furthermore, because of no CEA mode in the CCCM, the technique to ensure that γ at the inverter will not sink below the reference value which causes the risk of the commutation failure is described as well. The advantages of the CCCM in comparison with the MCCM will be demonstrated by using a back-to-back HVDC. To compare the results of using the MCCM and the CCCM, studies show the system recovery after three-phase fault to ground and the AC voltage transients when reactive power elements FC/FR are switched.

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II. Basic Concept of MCCM and its Behaviors during AC Voltage Reduction

The completed U_d-I_d characteristic of the MCCM is shown in Fig. 1. In normal condition the rectifier and the inverter operate in the CC and the VC mode respectively. The intersection of the CC and the VC determines the normal operating point of the HVDC represented as A_0 in Fig. 1.

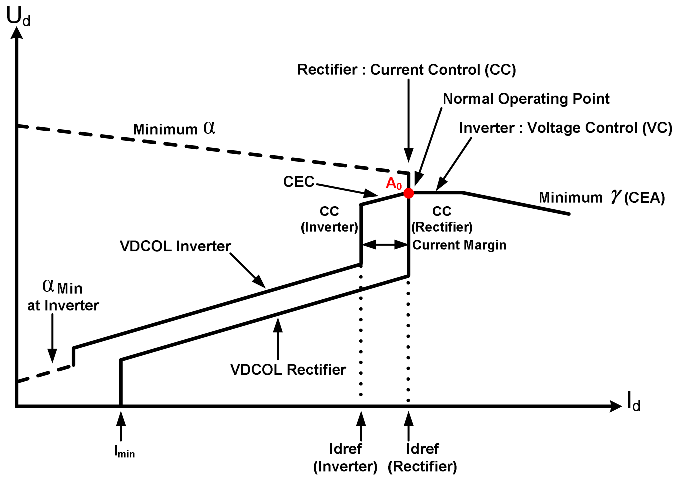

Fig. 1. MCCM U_d-I_d characteristic including VDCOL

It can be observed in Fig. 2 that when AC voltage reduction at the rectifier being greater than e.g. 5% of the rated voltage occurs, the rectifier will stay at the minimum firing angle (α) e.g. 5° and the minimum firing angle characteristic will drop along with the AC voltage reduction. As the result the inverter will become responsible for the CC instead of the rectifier. At this moment the system will operates at the temporary operating point defined as A_1 in Fig. 2. The change of the inverter control from the VC to the CC mode causes power deviation although the CEC is used for the smooth transition.

Moreover, if the current margin is large, the mode shift can result in a large power change which is an undesirable condition particularly in the weak AC systems where the systems are very sensitive to the change of the active and reactive power from the HVDC system. However if the current margin becomes small, it could happen that that the rectifier and inverter continuously shift current control back and forth due to the current harmonics which may be superimposed onto the DC current. The current margin is therefore typically about 10% of the rated current which is large enough to avoid the interaction of the CC.

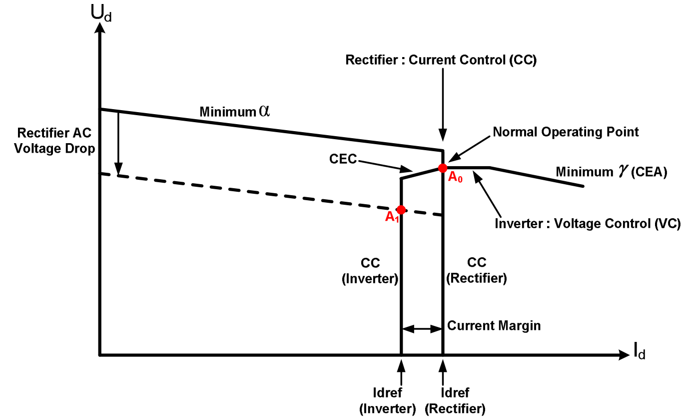

Fig. 2. MCCM U_d-I_d characteristic without VDCOL when Rectifier AC Voltage Drop

Considering the AC voltage reduction at the inverter in Fig. 3, its VC observes the reduction in the DC voltage. The control increases α (reducing γ) to keep the voltage constantly. If the inverter AC voltage remains reduced, the inverter shifts from VC to CEA mode and stays at the minimum γ reference. However if the AC voltage fall cannot be compensated by reducing γ to its minimum reference, then the DC voltage will drop along with the falling AC voltage. As a result the operating point will move transiently from A_0 to A_1 shown in Fig. 3.

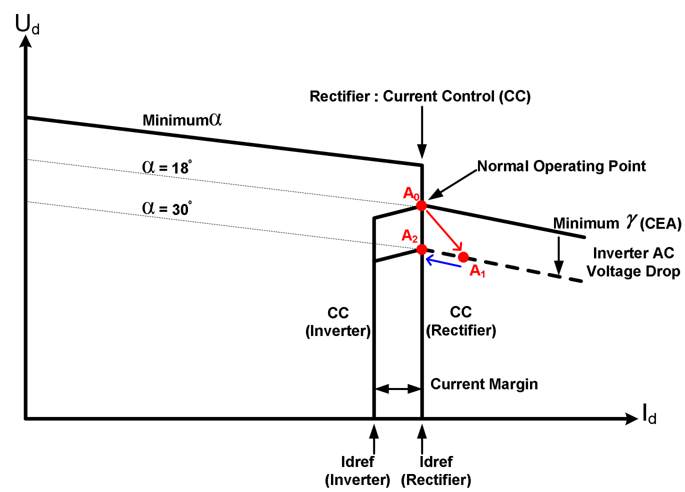

Fig. 3. MCCM U_d-I_d characteristic without VDCOL when Inverter AC Voltage Drop

The hierarchical power controller at the rectifier keeps on providing the constant I_{dref} due to its slow dynamic, therefore α at the rectifier will increase e.g. 30° to fulfill the I_{dref}. Consequently, the operating point moves from A_1 to A_2 shown in Fig. 3 and the present power is less than the desired power at the normal operating point indicated by A_0. This means the control cannot do anything till a few seconds or less in duration the inverter AC voltage recovers, the operating point will move upwards to A_0. However if the inverter AC voltage remains lower for longer time, the tap changer control will be activated to rise AC voltage on secondary side of the transformer connecting the converter to fulfill the normal operating conditions again. Nevertheless, the small portion of DC power reduction occurs for some times. This however does not occur in the new control concept.

Furthermore, when the disturbances e.g. the AC voltage reduction at the rectifier or the inverter station occur, it is not helpful to maintain the full load DC current particularly in a very weak AC system because of relative high demand of the reactive power consumption which increases further the reduction in the AC voltage causing also difficult recovery. Therefore the modification of the U_d-I_d characteristic is used by adding the **V**oltage **D**ependent **C**urrent **O**rder **L**imit (VDCOL) to reduce the DC current when the DC voltage falls to a certain level shown in Fig. 1.

Evidently, there are the disadvantages in using the MCCM due to the mode shift, possible mode chatter, slow dynamic of power control and loss of portion of power during the continuous AC voltage reduction at the inverter. The CCCM explained below offers the enhancement of these difficulties.

III. Basic Concept of CCCM and its Behaviors during AC Voltage Reduction

According to the new method, the rectifier controls power directly and the inverter functions as the equivalent resistance control only. Without the hierarchical power control, the fast dynamic of the power control can be achieved. Moreover, as the inverter consists of the equivalent resistance control only, the mode shift cannot occur. Furthermore, there is no mode chatter because the current margin is not considered. The completed U_d-I_d characteristic of the CCCM is shown in Fig. 4.

Theoretically, the DC power is the product of the DC voltage and the DC current. If there is no different between the measured values and the reference values, the HVDC will fulfill its setting power. Therefore, the rectifier and inverter in CCCM control simultaneously consider both voltage and current.

The rectifier power control characteristic combining the current and voltage errors is represented in (1)

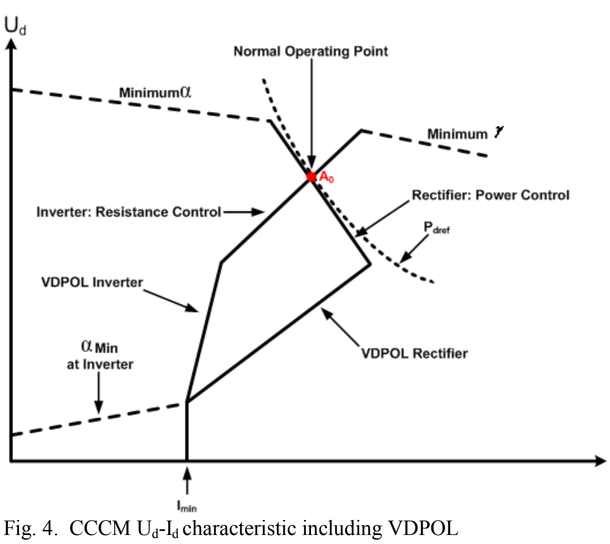

Fig. 4. CCCM U_d-I_d characteristic including VDPOL

$$(1-\frac{I_d}{I_{dref}})+(1-\frac{U_d}{U_{dref}})=0 \tag{1}$$

where

$1-\frac{I_d}{I_{dref}}$ = DC current error

$1-\frac{U_d}{U_{dref}}$ = DC voltage error

I_d = measured DC current

U_d = measured DC voltage

I_{dref} = reference DC current

U_{dref} = reference DC voltage

The summation of the current and the voltage errors is fed into the PI controller of the rectifier station. It can be seen that (1) is always a tangent of rectangular hyperbola DC power reference for all operating points shown in Fig. 4.

For the equivalent resistance control at the inverter, the current and the voltage errors are considered simultaneously but the current error is subtracted by the voltage error then the difference is fed into the PI controller. The characteristic of the equivalent resistance control at the inverter shows in (2).

$$(1-\frac{I_d}{I_{dref}})-(1-\frac{U_d}{U_{dref}})=0 \tag{2}$$

It can be seen that the CCCM has no need for CEA mode like the MCCM. The inverter in the CCCM however will not be harmed from commutation failures since it uses the calculated maximum α determined by (3) and (4) to ensure that γ at the inverter will not be lower than a reference extinction angle e.g. 18° in steady state condition.

$$\beta_{\min}=\cos^{-1}\sqrt{\cos^2(\gamma_{\min})-\cos^2(\gamma)+\cos^2(\alpha)-2(P_{dref}-P_d)} \tag{3}$$

$$\alpha_{\max}=180-\beta_{\min} \tag{4}$$

where

$\beta_{\min}$ = minimum advance angle

$\gamma_{\min}$ = reference extinction angle

γ = measured extinction angle

α = measured firing angle

P_{dref} = reference DC power

P_d = measured DC power

Furthermore, the calculation of the inverter will determine a suitable DC reference voltage (U_{dref}) shown in (5) which is not only be used for the inverter but also sent to the rectifier to operate at this U_{dref} to avoid the commutation failure at the inverter. It is evident that the inverter always coordinates with the rectifier. As a result the CCCM has less instability in comparison with the MCCM.

$$U_{dref} = U_d \frac{\cos\gamma_{\min} + \cos\beta_{\min}}{\cos\gamma - \cos\alpha} \qquad (5)$$

To explain the behavior of the rectifier and the inverter in the CCCM, the AC voltage reduction at either rectifier or inverter is considered.

The AC voltage reduction occurring at the rectifier is explained in Fig. 5. Power control performs its function by decreasing α to keep the DC voltage at the reference value. Once the α touches the minimum value e.g. 5º, it cannot further reduce itself and stays at the minimum value. If the AC voltage falls further, DC voltage at rectifier will drop resulting in the reduction in the DC current. The rectifier characteristic moves downwards from the normal operating point (A_0) to the temporary operating point (A_1) as shown in Fig. 5.

Comparing with the MCCM concept (Fig. 2), the CCCM control has no mode shift which could possibly cause the instability.

Considering back-to-back HVDC when the AC voltage drops at the inverter explained in Fig. 6, the equivalent resistance control will try to keep the DC voltage at the inverter by increasing α (reducing γ). When the minimum γ is reached, α cannot be increased further. Therefore if the AC voltage decreases further, the DC voltage at inverter will drop following the inherent characteristic of the extinction angle which results in the transiently increasing the DC current shown as the point A_1 in Fig. 6. The inverter calculates the suitable reference voltage and send to the rectifier. This causes the change in the rectifier slope and gets the temporary operating point defined as A_1 which is still located on the same rectangular hyperbola of the DC power reference as A_0. This means the transmitted power does not change.

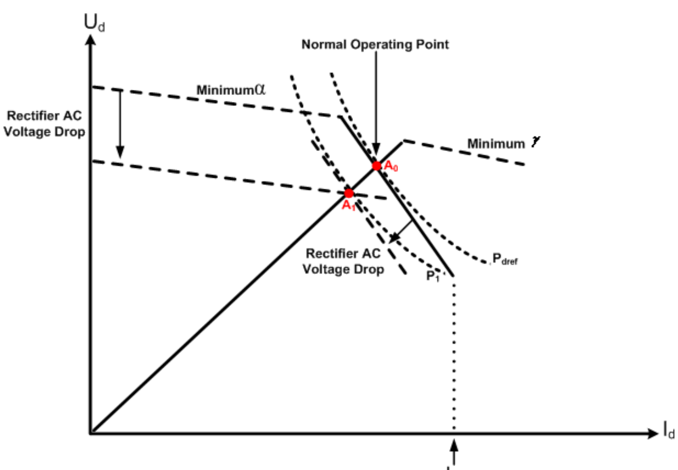

Fig. 5. CCCM U_d-I_d characteristic without VDPOL when Rectifier AC Voltage Drop

Comparing with the MCCM concept in Fig. 3, the power in case of the CCCM is constant and no mode shift like in the MCCM.

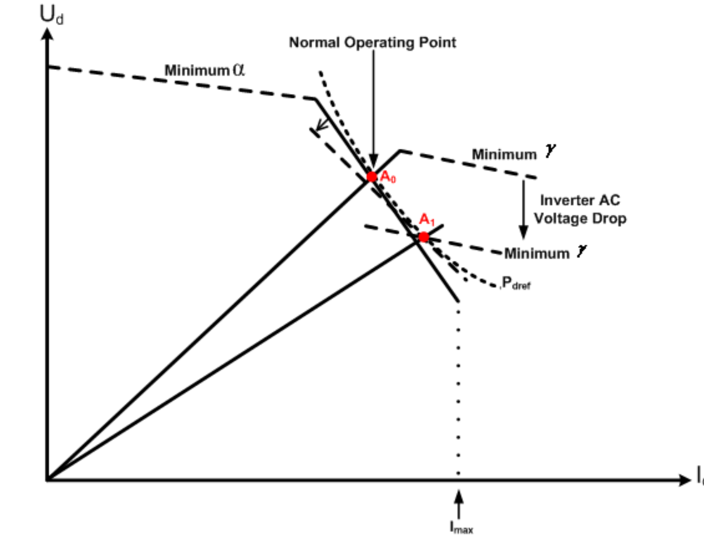

Fig. 6. CCCM U_d-I_d characteristic without VDPOL when Inverter AC Voltage Drop

Furthermore, when the large reduction of AC voltage occurs, the CCCM has the **V**oltage **D**ependent **P**ower **O**rder **L**imit (VDPOL), instead of VDCOL in MCCM, to decrease the DC power and, subsequently, the DC current. This is the benefit for system recovery. Fig. 4 shows the CCCM U_d-I_d characteristic including the VDPOL.

IV. Comparison of MCCM and CCCM in Back-to-Back HVDC

The reactive power is required for the commutation process in the line-commutated converter e.g. the HVDC using thyristors. The sources of the reactive power can be provided from the AC filters, the synchronous compensators, the static compensators and the fixed capacitors. As the demand of the reactive power is based on the HVDC operating point, the reactive power must therefore be supplied at the right time and also during power ramping.

The studied back-to-back HVDC connects the systems “A” and the “B”. The reactive power is provided by FC/FR switching on/off when the power transmits from the A to the B. However, the switching of the FC/FR elements can cause large AC voltage transients which lead to the undesirable conditions, in particular in the weak AC systems.

Two studies have been performed on the basis of the digital computer simulation approach with the PSCAD/EMTDC software package. The first one shows the comparison of the power recovery using MCCM and CCCM controls after three-phase to ground fault. The second one shows the comparison of the AC voltage transients caused by FC/CR switching when MCCM and CCCM control are used.

The first study investigates the performance of the HVDC control to recover the systems after three-phase to ground fault. Power flows from the A to the B. The fault occurs on the reading at 1s, on the B system close to the inverter station with successful three-phase auto-reclosure of the faulty line. The auto-reclosure dead-time is set to 0.5s.

It can be observed from Fig. 7 that during the recovery starting at 1.5s the transmitted powers of both MCCM and CCCM do not ramp smoothly because of the switching of FC/FR to supply the reactive power for commutation process. The recovery time is normally specified when power reaches to 90% of pre-fault power. This time is 1.9s (from 1.5s to 3.4s) for the CCCM and 3.3s (from 1.5s to 4.8s) for the MCCM. It is worth mentioning that the given AC system conditions are weak and the ramping set in the simulation is slow to avoid the problems caused by reactive power elements switching, the recovery time after the fault is therefore longer than normal in both cases. Nevertheless, the advantage of the new control at power recovery compared with the conventional control is evident.

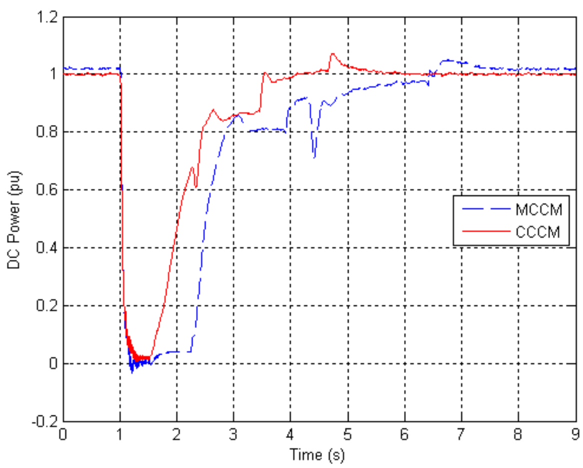

Fig. 7. Comparison of MCCM and CCCM for power recovery after three-phase to ground fault

For the second study, power is transmitted from the A to the B system where FC/FR will switch on/off to supply the reactive power for the inverter. However, the switching of the FC/FR can cause AC voltage transients. The control therefore has to react fast to attenuate the voltage transients which may cause an undesirable condition e.g. flicker.

When power ramps up, the FR will switch off first to increase the reactive power. If needed, the systems will however request for additional reactive power, and the FC1 and the FC2 will sequentially switch on.

The results show the B voltage transients when the FC/FR of B switching on/off. Fig.8-10 and Fig.11-13 show the results using the MCCM and the CCCM, respectively. The graphs shows DC power, DC current, DC voltage, AC voltage in the system B and the status of the FR, FC1 and FC2 on the B system.

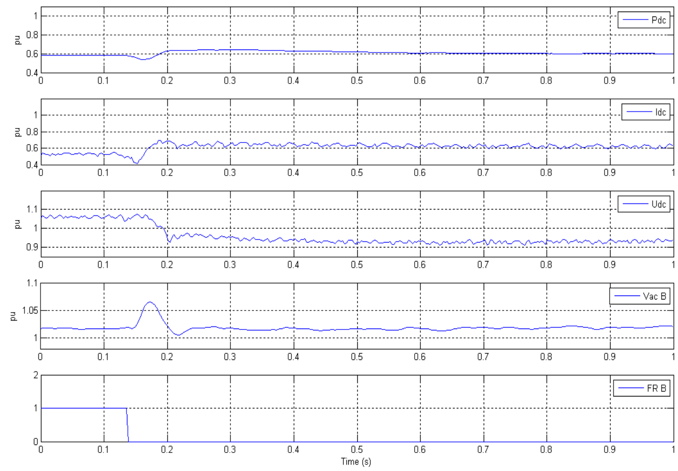

Fig. 8. FR of B switches off with MCCM

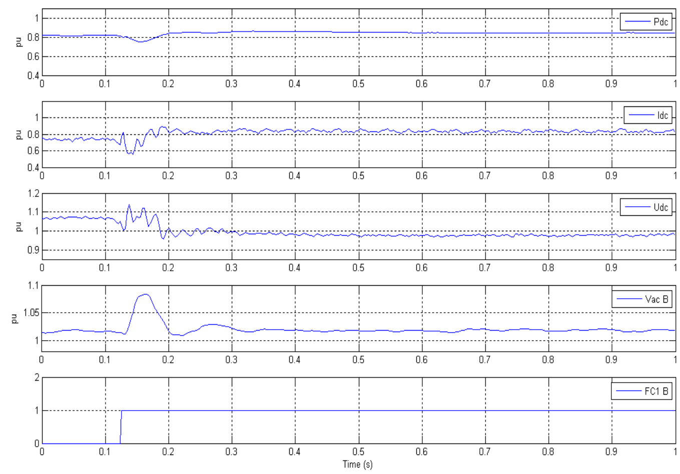

Fig. 9. FC1 of B switches on with MCCM

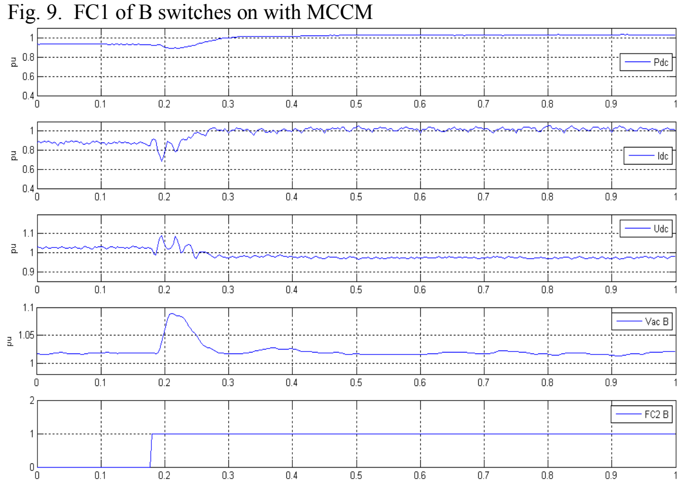

Fig. 10. FC2 of B switches on with MCCM

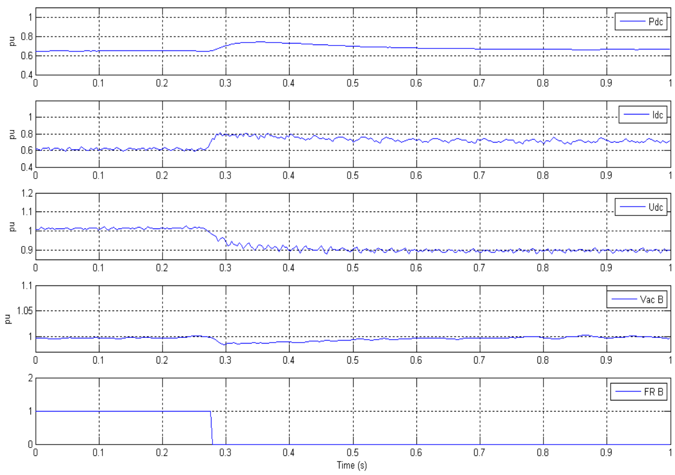

Fig. 11. FR of B switches off with CCCM

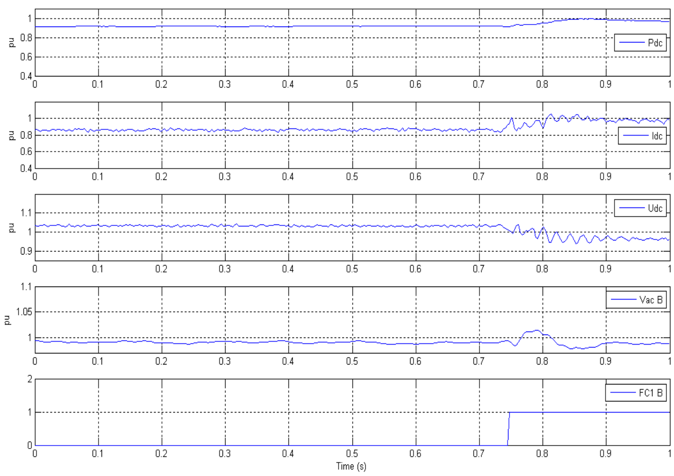

Fig. 12. FC1 of B switches on with CCCM

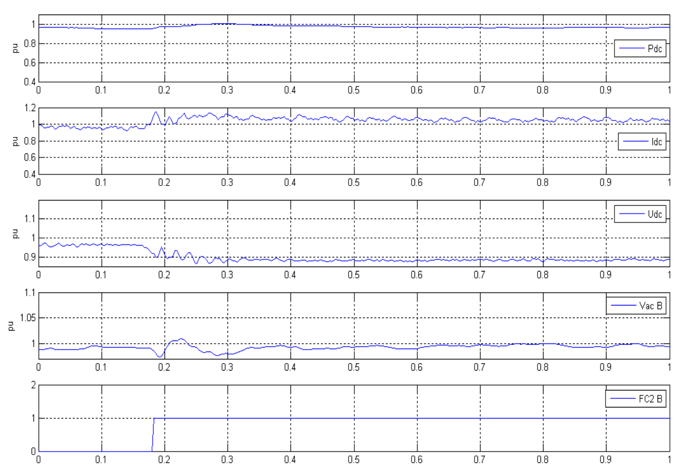

Fig. 13. FC2 of B switches on with CCCM

The comparison of the maximum peak-to-peak AC voltage transients in the B system during FC/FR on/off when used the MCCM and the CCCM are shown in Table I.

TABLE I
COMPARISON OF AC VOLTAGE TRANSIENTS ON B SYSTEM WHEN USED MCCM AND CCCM DURING FC/FR ON/OFF

	MCCM		CCCM	
	Max. peak-to-peak (pu)	%	Max. peak-to-peak (pu)	%
FR off	1.065-1.005	5.9	0.999-0.984	1.5
FC1 on	1.083-1.009	7.3	1.014-0.978	3.6
FC2 on	1.089-1.016	7.2	1.009-0.973	3.4

It can be seen that the use of CCCM is more effective than MCCM to damp the AC voltage transients at FC/FR switching. Using the CCCM the AC voltage transients are reduced by 74.6%, 50.7% and 52.8% respectively compared with the use of the MCCM.

V. Conclusions

It has been shown that the new CCCM control concept can improve the disadvantages occurring in the conventional control concept: mode shift, possible mode chatter, slow dynamic of power control and loss of power during the continuous AC voltage reduction at the inverter.

The studies with the back-to-back HVDC scheme show that the faster power recovery after three-phase to ground fault is observed when the new control concept is used. The studies further confirm the benefits of the new control concept to diminish the disturbances due to the switching of the FC/FR. It is shown that the new control concept can react fast and effectively damp the AC voltage transients caused by the switching.

VI. References

[1] D. Povh, I. Pyc, D. Retzmann, M. G. Weinhold, “Future Developments in Power industry”, The 4th IERE General Meeting and IERE Central and Eastern Europe Forum, October 17-21, 2004, Krakow, Poland

[2] G. Beck, D. Povh, D. Retzmann, E. Teltsch, “Global Blackouts – Lessons Learned”, POWER-GEN EUROPE 2005, 28-30 June 2005, Milan, Italy

[3] Wilheln D., Piwko R. J., “High Voltage Direct Current Handbook, First Edition”, EPRI 1994

[4] F. Karlecik-Maier, “A New Closed Loop Control Method for HVDC Transmission”, *IEEE Transactions on Power Delivery*, Vol. 11, No. 4, October 1996, pp. 1955-1960

VII. Biographies

Dusan Povh was awarded the degree of Electrical Engineer by the University of Ljubljana, Slovenia in 1959 and his doctor degree at the Technical University Darmstadt, Germany, in 1972. Since 1985 he has been professor at the University of Ljubljana. In 1995 he was appointed Guest-Professor at Tsinghua University, Beijing, PR China.

He has been working for Siemens in different leading positions for many years and is now an independent consultant. His main fields of interest are power systems and power electronics. In his carrier he published more than 200 international papers.

He is Fellow of IEEE and Honorary Member of CIGRE. He served for 6 years as the Chairman of CIGRE Study Committee on HVDC and FACTS. He received two prestigious awards from IEEE: Uno Lamm Award for achievements in the field of HVDC in 2001, and FACTS Award for his contributions to this technology in 2003.

Pakorn Thepparat was born in Ratchaburi, Thailand in 1978. He received the B.Eng. degree at Kasetsart University, Thailand in 2001 and the M.S. degree at RWTH Aachen, Germany in 2006. Both degrees are in Electrical Engineering.

He worked for EGAT -- Electricity Generating Authority of Thailand -- (2001-2003) in Transmission Control System Development Department, Transmission System Maintenance Division and was responsible for HVDC SCADA systems. He is currently pursuing his PhD degree at the Technical University of Ilmenau, Germany.

His research interests are HVDC control and power system analysis.

Dirk Westermann (M'94–SM'05) was born in Germany in 1968. He received his diploma degree in Electrical Engineering in 1992 and his Ph.D. in 1997 at the University of Dortmund, Germany.

In 1997 he joined ABB Switzerland Ltd. where he held several positions in R&D and Technology Management. He became full time professor and head of the power system department at the Technical University of Ilmenau, Germany in 2004. There he has been the director of the Institute of Electrical Power and Control Technologies since 2005. He is author of more than 40 international scientific publications and holds international patents for power system planning and control. He worked on research projects related to FACTS devices, power quality, power system analysis and control and energy management systems. His current research interests are power system analysis and control HVDC, FACTS, wide area measurement and demand side management in interconnected systems, energy management systems and control and operation of decentralized systems.

Prof. Westermann is senior member of IEEE, regular member of CIGRE SC B4 and member of VDI. He is involved IEEE as member of the executive committee of IEEE Germany Section and the IEEE Power Engineering Society Chapter Germany. He is past chairman of the IEEE Power Engineering Society Chapter Switzerland. Furthermore, Prof. Westermann is convener of CIGRE WG B4.46.