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Enhancement of Power System Stability in Future Power Transmission System Using Various Controllers and HVDC System

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Abstract:

Bulk Abstract- As a consequence of the fast development of renewable energy sources in the UK, higher transmission capacity will be required to integrate potentially large volumes of wind generation in the future. Also, over the next decade, maintaining the transmission system security and stability will become more difficult. A major increase in the application of HVDC transmission technology and the deployment of series compensation within the existing AC transmission system is expected to provide the required transfer capability in the future. However, there is also a need to employ smarter ways of operating these power flow control devices. Firstly, this paper investigates the capability of the HVDC link in improving the inter-area power oscillation damping. Two approaches in the design of power oscillation damping controller are demonstrated. Secondly, the paper presentsthe application of the HVDC links set-point adoption for the stability enhancement through a novel non-parametric control system design approach using the sample regulator control design method. This method is mainly attractive for applications in large integrated power systems since the controller design only requires knowledge of the nonparametric model of the power system i.e. the open-loop step response, which is easily obtainable compared to development of parametric model of the power system.

Index Terms:
Power System Stability, HVDC Transmission Link and Sample Regulator.

I. INTRODUCTION:

Based on the legislation on renewable energy and Green House Gas Emissions (GHGE), EU and UK governments are committed to reducing CO2 emissions by increasing the level of the energy being produced from renewable sources up to 15% by 2020. It is suggested that the 15% renewable energy target could be met by a 30% renewable contribution in the electricity generation [1]. Consequently, the volume of wind generation is expected to increase over the coming years. Since the majority of the new wind generation will be in Scotland, there will be a significant increase in the power transfer capability requirement across the Anglo-Scottish boundary (between Scotland and England) which is currently limited by stability constraints and managed by limiting the power transfer across the boundary. One of the potential means of accommodating significantly increased power flows across Anglo-Scottish boundary would be through the Western HVDC link (with capacity of 2.2GW) which will come in to operation by 2016. The Western HVDC link would provide sufficient transmission capacity until 2018-2019 after this point further reinforcement would be required.

Therefore, the East Coast HVDC link is planned to come in to operation by 2018 to provide an additional 2.1GW of capacity [2]. Although, the East and West HVDC links will add to the current transmission capacity, it is necessary to look towards smarter ways of operating the transmission network and gaining additional benefit from the DC links in stability enhancement in order to meet the increasing challenge of accommodating large amounts of variable renewable generation. The HVDC Links can be implemented for both transient stability enhancement and power oscillation damping improvement using various control schemes, such as the supplementary damping controller or the set-point adoption of the HVDC links at the post-fault. The main focus of the paper is to investigate the capability of the HVDC links in improving both transient and dynamic stability. In this paper, firstly the capability of the HVDC link in improving inter-area power oscillation damping is investigated.

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Also, two approaches in design of the damping controller for the HVDC link are demonstrated. A comparative study on their performances is then presented. Finally, in section VIII, the application of HVDC link's set-point adoption for transient stability enhancement is presented through a close loop control system using a novel sample regulator control design method.

II. INTRODUCTION TO TRANSIENT AND DYNAMIC INSTABILITY IN GBTRANSMISSION SYSTEM:

Since 1980 the GB system has experienced large low frequency oscillations (around 0.5HZ), due to the fact that generator groups in the Scottish network oscillated against generator groups in the network of England and Wales. Following some post-event analysis, it was recognized that the oscillation damping reduces as the power flow increases across this boundary. Therefore, a limit on the level of power transfer across the Anglo-Scottish boundary was set and consequently capacity was severely constrained. Due to the recurrence of large sustained oscillations, Power System Stabilisers (PSS) were consequently installed on a couple of Scottish generators, [6]. However, due to the dynamic characteristics and uncertainty in dynamic network simulation, there is still a significant constraint in the export of power from Scotland to England [4]. Furthermore, in order to monitor the inter-area modes and detection of any oscillations between England and Scotland, a system was developed, by Psymetrix which is capable of performing constant oscillation analysis and determining the frequency, amplitude and damping of the modes of oscillation. The current system has

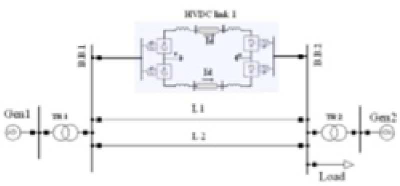

Fig.1. Test system in PowerFactory

The ability to identify whether the oscillation damping on the system has dropped below predefined stability margins. On identifying any unacceptable damping an alarm is generated to alert the system operators that the system may be approaching instability. In the case of such an alert, the Scottish transfer is to be reduced in 100MW blocks, until the dynamic stability monitor returnsto the stable region [8].

However, reducing the power flow across the interconnection is not considered to be an economical and effective solution. Therefore, in the future a more economical approach such as employing advanced wide area power oscillation damping controller or an overall stability control system is required, in order to enhance the transfer limit across the network.

III. PRINCIPLE OF MODALANALYSIS:

A nonlinear model of the power systems can be linearized around an operating point as presented in the state space format in (1):

$$\Delta X^{\bullet} = A\Delta X + B\Delta u \qquad (1)$$
$$\Delta y = C\Delta X + D\Delta u$$

The transfer function of above system can be defined in terms of input and output matrices and right and left eigenvectors as presented in (2). Ri is the residue of a specific mode which gives measure of that mode's sensitivity to a feedback between the output (y) and the input (u). It is in fact the product of the mode's observability and controllability [9]. The rest of the parameters are defined in Table I.

$$G(s) = \frac{\Delta y(s)}{\Delta u(s)} = \sum \frac{C\phi(:,i)*\Psi(i,:)B}{(s-\lambda_i)} = \sum \frac{R_i}{(s-\lambda_i)} \qquad (2)$$

The real part of the eigenvalue of the system gives the damping, and the imaginary part gives the frequency of oscillation. In general, the oscillatory modes having damping ratio less than 5% are considered to be critical

TABLE I
DEFINITION OF THE PARAMETERS

ΔX	State vector	A	State matrix	λ_i	Eigenvalue
Δy	Output vector	B,C	Input and output matrix	Φ	Right eigenvector
Δu	Input vector	D	Feedforward matrix	Ψ	Left eigenvector

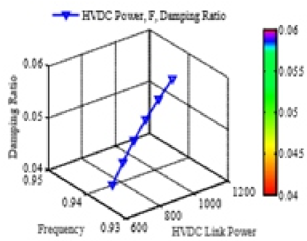

Fig.2. Impact of the HVDC link power flow variation on the damping ratio of the oscillation mode

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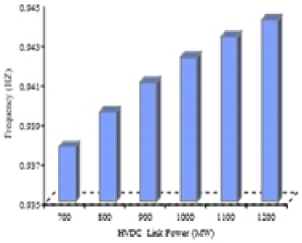

Fig.3. Impact of the HVDC link power flow variation on the frequency of the oscillation mode

IV.THE TEST SYSTEM UNDER THE STUDY:

All the studies have been performed in DIgSILENT PowerFactory using a Single Machine-Infinite Bus (SMIB) test system, shown in Fig.1. This model represents the transmission network connections between the North of England and Scotland. In this test system 1.5GW of power is transferred from Generator 1 to load and the HVDC link carries 500MW of power. The HVDC link is modeled as a bipole CSC-HVDC link. Also, a dynamic model of the generator is implemented in this test system. A model analysis for the two-area system under the study was performed and results showed that the system is stable. However, it has one inter-area oscillatory mode with damping ratio less than 5%.

V.IMPACT OF THE HVDCLINKON SYSTEMSTABILITY:

The impact of sharing active power flows between the DC link and the AC lines on the movement of poorly damped inter-area oscillation modes was investigated prior to adding any damping controller to the HVDC control scheme. It was observed that as the active power on the DC link is gradually increased from 600MW to 1.2 GW and more power is pushed from the AC lines to the DC link the synchronizing and damping ratio are increased (Fig.2) which consequently results in improving the dynamic stability of the network. Also, as it can be seen in Fig.3 the frequency of the poorly damped oscillatory mode increases by increasing the power flow on the HVDC link.

VI. SUPPLEMENTARY DAMPING CONTROLLER DESIGN FOR THE HVDCLINK

Low frequency oscillations are inherent in large integrated power systems. To improve the damping of oscillations in the power systems, a supplementary power oscillation damping control can be employed for existing devices such as FACT devices or HVDC links. The supplementary control of the HVDC link, which provides modulation to the rectifier current controller, is an effective means for the mitigation of interarea oscillations of interconnected power systems [9].In this study, two approaches for the design of power oscillation damping controller are presented. The first presented supplementary damping controller for the HVDC link is a PSS-based damping controller which has similar structure of generators' PSS, incorporating phase compensation block, washout filter, gain and limiter. In the second approach, a simple PI controller is used as a damping controller for the HVDC link. The overall structures of the both damping controllers are presented in the next section. A.PSS-based damping controller design for the HVDC link An ideal damping controller shifts the selected eigenvalue of the system into the left side of the complex plan in order to make the system stable and improve the system oscillation damping. The selected mode of interest must be both controllable by the chosen input and observable in the chosen output for a feedback control to have any effect on the mode. Therefore, selection of suitable feedback variables is critical to the design of any damping controller. In this study, the difference between generators speed is implemented as an input signal for the damping controllers. Fig4. and Fig.5. show the models of the PSS /PI-based damping controllers respectively. The damping controllers send the control signals to both poles of the HVDC link. Also, it is proven that the amount of the shift of the selected eigenvalue (Ʒ) that is caused by the feedback damping control is proportional to the transfer function of the feedback control and the residue (Ri) of the selected eigenvalue. Therefore, in this design a residue based method is used for tuning the damping controllers [9]. B.PI-based damping controller design for the HVDC link In the second approach, a PI controller is implemented in design of supplementary oscillation damping controller. The advantage of this approach is due to the fact that controller has less parameters to be tuned. The comparison on performances of the both damping controllers is presented in sectionVII.

VII.SIMULATION RESULTS AND ANALYSIS ON PERFORMANCE OF THE DAMPING CONTROLLERS:

Modal analysis is performed for the test system with the integrated HVDC link in order to identify the oscillatory modes of the system under study.

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The modal analysis results revealed an inter-area oscillation mode with damping ratio of 4%. Hence, a damping controller is added to the HVDC control system to investigate the effect of damping controller on moving the poorly damped oscillatory mode to the left side of the complex plane. Three study cases are conducted to investigate the performance and capability of both damping controllers in the enhancement of the system stability. For the first study case (Fig.6.a) the performance of the both damping controllers and the system responsesare investigated following the occurrence of a small change to the system.

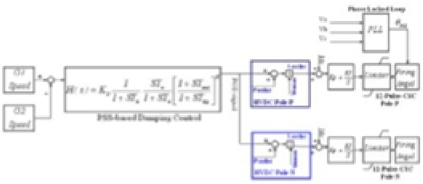

Fig.4. Supplementary damping controller for a bi-pole CSC-HVDC link

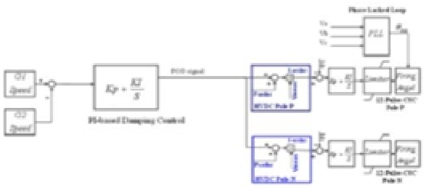

Fig.5. Supplementary damping controller for a bi-pole CSC-HVDC link

A small disturbance in the system is created by change of the HVDC link's set-point and increasing the power flow on the DC link from 500 to 700MW. In the second study case (Fig.6.b), the robustness of the damping controllers are examined by applying a large disturbance to the test system. A large disturbance in the system is created by applying a three phase fault on line 2. Finally, in the third study case (Fig.6.c), the impact of communication time delay, in providing the wide area input signals, on the performance and effectiveness of the PSSbased damping controller is explored by adding a time delay blocktothe main damping controller model. Fig.6.a. and Fig.6.b present the responses of the generator rotor angle, generator active power and AC line active power to small and large disturbances correspondingly. In both cases system responses with and without implementing a damping control are presented. It is evident from the results that both damping controllers improve the damping ratio of the oscillatory mode and improve the system oscillation damping significantly. Also, the simulation results confirm that both PI and PSS-based damping controllers are robust and remain effective in providing oscillation damping following the occurrence of a large disturbance (Fig.6.b).

Since wide area signals are often used as the inputs for the damping controller, the time delays related to their transmission required to be considered. Therefore, the impact of various time delays on the performance of the PSS-based damping controller for the HVDC link is investigated and presented in Fig.6.c. In this study case, different time delays ranging from no latency to 200 milliseconds latency are applied to the damping controller. It can be seen that the effectiveness of the wide area HVDC damping controller is decreased as the time delay is increased. In addition, when the time delay is increased to 200ms, the damping controller has a negative effect on the system power oscillation damping. After demonstrating the capability of the HVDC link's damping controller in improving the inter-area oscillation damping, in the next section of the paper, the application of the HVDC link's set-point adoption in improving the transient stability is presented implementing a novel Sample Regulator (SR) control design method for design of the secondary control system.

VIII.MULTI-VARIABLE SAMPLED REGULATOR:

In this section firstly, the need for the multivariable control system for the control of various power flow control devices in the power system is discussed and following that, the fundamental principle of SR control system design method will be introduced. The non-parametric approach applied to the power system coordination problem is a sampled multivariable control law which is based on the principle of a passivity energy system to ensure the closed loop system stability [11-12].

A. Requirement for multivariable control:

Internal control systems within the actuators i.e. HVDC links are primarily required to perform rapid power flow control. Secondary control is often used for servo-control systems where primary control can regulate the controlled variables around command points. Since the internal controllers from the manufacturers are usually based on the Single Input-Single Output (SISO) design and tuned only for a single control variable, the SISO design may be sufficient for the cases where the individual controls are near the 'optimal' on their own and variables under control in the system are relatively uncoupled. However, the built-in SISO controllers will not be able to coordinate several individual actuators and control all outputs.

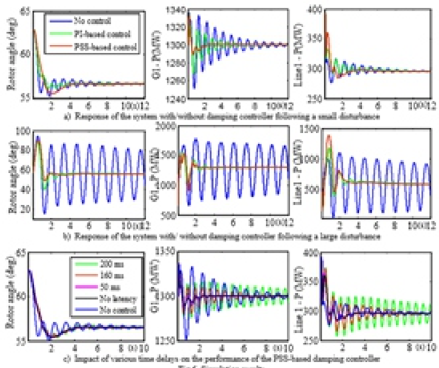

Fig.6. Simulation results

coherently in the feedback control system. With the presence of interactions the overall system stability and control performance can be severely compromised. Interactions in a real system may depend on the system operating conditions. Within power systems, planned or unplanned outages may change the interactions between control variables and sometimes this can be fairly rapid and severe. In these cases, control systems designed on the basis of the SISO control will be challenged.

B. Algorithm:

Consider a MIMO stable linear time invariant plant P with unit step response H (t) and with the sampling rate of T. The sampled output of the system is given by the output vector y (nT) as described in [11]-[13].

$$y(nT) = \sum_{r=1}^{n} \Delta H(rT)U((n-r)T) \quad (3)$$

$$\Delta H(rT) = H(rT) - H((r-1)T) \quad n = 0,1,2,.. \quad (4)$$

Where n=0, 1, 2... , and the input vector U (t) is defined as:

$$U(nT) = \begin{cases} 0 & t<0 \\ U(nT) & t \in [nT,(n+1)T] \end{cases} \quad (5)$$

Authors of the study presented in [11] developed a new method ensuring system stability by designing the closed loop system to be passive for the class of the sampled regulators of the form

$$U(nT) = C(y^0(nT) - y(nT)) + \sum_{r=0}^{n} b_{n-r}U_r \quad (6)$$

In this MIMO system U and y are vectors and C and b, with compatible dimensions, are constant matrices that are calculated as follows:

$$C = (I + \sum_{n=1}^{\infty} \varphi_n)H(\infty T)^{-1} \quad (7)$$

$$b_n = C\Delta H(nT) - \varphi_n \quad b_0 = 0 \quad n>0 \quad (8)$$

It is proven in [11] that if the sequence of ijn is selected to be passive the system with the sampled control law of (6) is asymptotically stable with zero Steady-State Error (SSE) with a quantifiable degree of robustness in the case of variations in the response H(t). Passivity of sequence Q is guaranteed if is real symmetric positive semi-definite such that converges and it also positive and semi-definite. One simple choice for such a passive sequence is a sequence of real positive semi-definite matrix

$$B\Gamma K + K\Gamma B = -(K\Omega + \Omega^T K) \quad (10)$$

Where;

$$\Gamma = \sum_{n=1}^{N} (\Delta H_n)^T (\Delta H_n), \quad K = H(\infty)^T H(\infty) \quad (11)$$

$$\Omega = \sum_{n=1}^{\infty} (\Delta H_n)^T (H_{n-1} - H(\infty)) \quad (12)$$

This choice of A ensures both the stability and the optimal dynamic performance and hence guarantees the system damping and the tracking speed. This approach is a multivariable system design method. It follows feedback control laws and is a natural extension of the traditional (sampled) integrating regulator. In fact the integrator controller is a special case in this class of SR

$$U_n = C(y_{ref}(nT) - y(nT)) + b_1 U_{n-1} \quad (13)$$

C. Main characteristics of the SR control:

Since all information required in the design is obtained in the time domain, this algorithm is suitable for implementation of a computer controlled system. This algorithm could be further developed into an adaptive self-tuning on-line control algorithm. The self-tuning implementation of this regulator is to address changes in the operating conditions and system configurations.

IX. SIMULATION RESULTS AND ANALYSIS ON PERFORMANCE OF THE SR CONTROL:

In this section, the application of HVDC link's set-point adoption in stability enhancement is presented using the SR control design method for design of secondary control. The main reason to implement SR controller for HVDC link's set point adoption at post-fault is due to the fact that the SR controller can be extended to a Multi-Input- Multi-Output (MIMO) controller which has the capability of co-coordinated control of various power flow control devices in the power system. However, in this paper, only the performance and robustness of a SISO, SR controller in stability improvement at post-fault is evaluated. In this study, the same test system presented in section IV is used to investigate the capability of SR control in maintaining and improving system stability at post-fault.

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Fig.7 shows the voltages at bus B.B.1 and bus B.B.2 as well as generator1 rotor angle and the speed of generator1 following the fault occurrence and loss of line 2. It can be seen from Fig.7. (Blue graphs) that following a fault occurrence without any control, the system become unstable.

Whereas, the system stability can be maintained at post-fault by compensating for the loss of the AC line through the HVDC link's set-point adoption using the SR controller (Fig.7. green graphs). The performance of the SR controller in maintaining stability at post fault is compared with the designed PSS-based damping controller.

Although, both damping and SR controllers could maintain the system stability at post fault, it can be seen in Fig.7. (Green graphs) that less voltage drops at both buses are observed when the SR controller is implemented.

X. CONCLUSION:

The capability of HVDC link in improving inter-area oscillation damping is investigated and two approaches in design of the power oscillation damping controller for the HVDC link are demonstrated. In addition, the application of HVDC link's set-point adoption is presented using a novel SR control design method for design of controller.

Also, a comparison study on the performance and effectiveness of both oscillation damping controllers and SR control in the system stability enhancement is conducted and presented. The simulation results demonstrate that both PI and PSS-based damping improve the system oscillation damping significantly. In addition, the results confirm that when the SR controller is implemented less voltage drops at buses are observed following a fault occurrence.

XI. FUTURE WORK:

In future, the next step of the research will be focused on the extension of SISO SR controller to design a robust, operational MIMO stability control system with multi objective regulating and tracking capability using the HVDC link for power flow tracking at pre-fault and post-fault. Since the Anglo-Scottish boundary is such a critical interconnection,

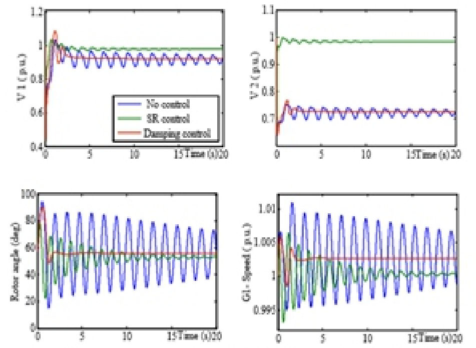

Fig.7.Simulation results on performance of SR controller and damping controller for stability enhancement at post fault

both traditionally (as it is limited by stability constraints) and forthcoming (due to the increasing renewable generation growth), National Grid has put a huge investment such as commissioning an embedded HVDC link and TCSC into this area to upgrade the network to increase power transfer capability across this boundary in order to accommodate the future renewable generation. As a result, an overall closed loop stability control system is required that firstly could reconcile with existing tools and control systems and secondly cater for the need of all upcoming and existing power flow and voltage control devices such as SVC, HVDC link with their associated POD control .

Also, such a system would ideally be aimed at addressing the issues of stability, coordination and optimization concurrently. The HVDC link and SVC are both fast and automatic controlled devices with different control objectives. On the whole the SVC regulates the voltage and the HVDC link primarily controls pre-fault power flow while at the immediate post fault the HVDC link fast ramping up dynamic and short term over- load capabilities can be utilized to enhance transient stability across the Scottish boundary.

The next step of this research is to develop a closed loop MIMO Sample Regulator to provide coordinated control of the HVDC links, SVC and TCSC under one framework at prefault and enhance the boundary stability limit at post-fault using the HVDC link post fault action. Finally, the control design method will be tested on the full GB transmission system for coordinated control of various types of control devices.

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