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Semi-Active Wide-Area Fault-Tolerant Control in Electric Power Systems

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Abstract: In this paper is presented a semi-active fault-tolerant control (SAFTC) as an alternative to reconfigurable or self-repairing fault-tolerant architectures with application to power systems. The final goal is to achieve stability and a minimum level of system performance following the completely loss of the feedback signals in the controller, which in this case are remote wide-area signals. The proposed controller is designed under the framework of Linear Matrix Inequalities (LMIs) to achieve pole placement. The semi-active design is compared against and ordinary or non-fault-tolerant control design to highlight that following the loss of a wide-area signal in the control, the closed loop response can lead to instability in the non-fault-tolerant case. The results are validated through nonlinear simulations results using a reduced version of the Nordic power system where the effectiveness of the proposed approach is demonstrated.

Keywords: Wide-area monitoring and control, control of energy systems, fault-tolerant control, linear matrix inequalities.

1. INTRODUCTION

The electric power grids are continuously growing, large, complex, dynamic systems - increasingly penetrated by fluctuating renewable energy sources. The conventional part of the system under control considered here consists further of components such as synchronous generators, transmissions lines and electric loads; just to mention a few of them defining the system's natural dynamic behaviour in the supply-demand balance. New electronic devices are often integrated into the system; such as flexible AC transmission systems (FACTS), convertors of high voltage DC systems (HVDC), phasor measurement units (PMUs) etc. The PMUs sample fast and time-synchronously voltages and currents; they make use of the global positioning systems (GPS) and require fast communication networks to make the best use of the data captured across the whole power system for monitoring and control. FACTS and HVDC can act as fast power electronic actuators to deal with dynamic phenomena such as power oscillations.

To match the rapid increase in demand for electricity, interconnections of large power systems became a very popular solution to increase the availability and reliability in supply of electric power. However, the increase of the electric power demand results in higher loading of the transmission lines and the network operators are often forced to operate the system very close to its stability limits. This requires more detailed investigations of the global system behaviour in order to maintain the security of the system, Breulman et al. (2000). The negative phenomena which may suddenly occur are voltage, transient and small-signal instabilities. They might lead to severe blackouts in the system, see e.g. Rogers (2000); Kundur (1994); Van Cutsem and Costas (2008) for more details.

The applications of modern control theory in power systems is an effective way how engineers can address the stability problems today, Zweigle and Venkatasubramanian (2013); Moradzadeh et al. (2013). The existing control in electric power systems consist of a number of nested, local loops that regulate different quantities in the system (for example, the system frequency or voltage magnitudes). The main task of these controllers is to ensure that the power system is operated within acceptable limits and the quality of power supply is preserved. Usage of fast sampled remote signals in these control loops can often improve the dynamic behaviour substantially but it has not become common practice yet. Challenges in the design of these devices have already been identified Mahmoud et al. (2003).

In the last decade, different working groups have demonstrated the effectiveness of using wide-area signals and modern control techniques to deal with small-signal stability problems in energy systems, see Werner et al. (2003); Nguyen-Duc et al. (2010); Li et al. (2012); Mokhtari et al. (2013); Chaudhuri et al. (2010); Zhang and Bose (2008); Zima et al. (2005); Korba et al. (2007). Their work have concentrated on different aspects such as dealing with time delays Chaudhuri et al. (2004) in the feedback signals, adaptive features Korba et al. (2007), providing a low order controller Simfukwe et al. (2012) and the type of actuator used by the controller (FACTS/HVDC etc.) Mithulananthan et al. (2003), however very little has been reported considering the completely loss of these class of signals used as feedback in the controller.

Fault-tolerant control is a vast area of knowledge and can be applied to a wide range of problems. Within this area, it is possible to find in general two different types of schemes, active and passive ones. In the active schemes, several controllers are designed (one for each system condition). This class of schemes provide the best performance since each control is designed optimally for each particular condition, however its implementation is not simple because it requires switching according to the specific condition. On the other hand, passive architectures are simple to implement, however designing such controllers require more sophisticated control techniques that might be conservative, furthermore if the number of different scenarios is large, a solution to the problem might be very difficult to find or it even does not exist at all.

An alternative to reliable and self-designing fault-tolerant architectures is presented in this work. The proposed scheme provides a unique controller designed simultaneously for multiple operating conditions with time-invariant parameters and a simple switch in the control structure is required, therefore referred as semi-active approach.

The paper is organized as follows, the formulation of the problem is presented in section 2, here the loss of wide-area signals is modeled using a diagonal matrix at the output of the system. Two control strategies are described, a non fault-tolerant controller (ordinary approach) and a semi-active fault-tolerant controller, both base on LMIs. The architectures described in subsections 2.1 and 2.2 are validated in section 3 through dynamic simulations of the reduced Nordic power system model. A summary of the work is presented in Section 4.

2. FORMULATION OF THE PROBLEM AND CONTROL APPROACH

Given the state space representation of a linear time-invariant (LTI) system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \\ G(s) &\stackrel{s}{=} \left[\begin{array}{c|c} A & B \\ \hline C & 0 \end{array}\right] \end{aligned} \tag{1}$$

where $x \in \Re^n$ are the states, $u \in \Re^q$ the input and $y \in \Re^p$ the output of the system. The matrices $A \in \Re^{n\times n}$ are the state matrix, $B \in \Re^{n\times q}$ the input matrix and $C \in \Re^{p\times n}$ is the output matrix of the system, respectively. The loss of wide-area signals is represented by the following set of systems

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y_i(t) &= \Delta_i Cx(t) \\ G_i(s) &\stackrel{s}{=} \left[\begin{array}{c|c} A & B \\ \hline \Delta_i C & 0 \end{array}\right] \end{aligned} \tag{2}$$

where the matrix $\Delta_i(t)$ is a diagonal matrix and is used to model sensor faults (loss of wide-area signals) with $\Delta(t) \in \mathbf{\Delta}$ where

$$\mathbf{\Delta} := \{\Delta(t) = diag(\delta_1(t), \ldots, \delta_p(t)) : \delta_j(t) \in \{0, 1\}\ \}. \tag{3}$$

Note that $\Delta_1(t) = I_p$ if all wide-area signals are available and $\Delta_m(t) = 0_p$ if all signals have failed. It should be noted that there are 2^p possible combinations of signal failures so that $i = 1, \cdots, m$ where $m = 2^p$. If a fault occurs in the communication system, the loss of the jth wide-area signal can be modeled by setting the jth element of $\Delta_i(t)$ equal to zero, i.e. $\delta_j(t) = 0$. The general concept is shown in Figure 1.

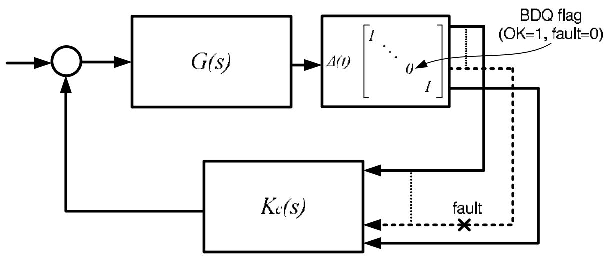

Fig. 1. General concept: the diagonal matrix $\Delta(t)$ is used to model the loss of wide-area signals (BDQ-Bad Data Quality).

The design of ordinary and semi-active fault-tolerant controllers is considered in this paper. The reconfigurable or self-repairing control design problem consists of compensating the impact of the failures designing an individual controller for each fault scenario, e.g. You et al. (2006). In some applications, this principle may not be feasible, for instance in energy systems as described later.

2.1 Ordinary Control

An ordinary controller (OC) is an architecture designed to satisfy a desired level of dynamic performance under fault-free conditions, e.g. when all remote wide-area signals are available. Under fault-free conditions this class of controllers are expected to provide satisfactory performance. However, following the loss of one ore more feedback signals can significantly degrade the performance of the controller to the point of instability. The OC is designed to achieve pole placement using linear matrix inequalities (LMIs) to include additional constrains. Subsequently, similar methodology is used for the design of the semi-active fault-tolerant controller (SAFTC) to ensure a fair comparison in terms of design and performance.

The state space form of the controller is described as follows

$$\begin{aligned} \dot{x}_c(t) &= A_c x_c(t) + B_c y(t) \\ u(t) &= C_c x_c(t) \\ K_c(s) &\stackrel{s}{=} \left[\begin{array}{c|c} A_c & B_c \\ \hline C_c & 0 \end{array}\right] \end{aligned} \tag{4}$$

where $A_c \in \Re^{n\times n}, B_c \in \Re^{n\times p}$ and $C_c \in \Re^{q\times n}$ are matrices of appropriate dimensions. The closed-loop state dynamics of this controller is described as $\dot{\tilde{x}} = \tilde{A}_i\tilde{x}$ where

$$\tilde{A}_i = \begin{bmatrix} A & BC_c \\ B_c\Delta_i C & A_c \end{bmatrix}. \tag{5}$$

Now, we present the design of the controller for the faut-free condition or nominal case ($\Delta_1(t) = I_p$). The goal of this controller is to place the closed loop poles of the system (5) within a pre-defined region of the complex plain. The theorem described bellow Chilali and Gahinet (1996) describes the problem.

Theorem 1. Let $i = 1$ so that $\Delta_1(t) = I_p$. Then $\tilde{A}_i$ is stable and all its eigenvalues lie on the left hand side of the predefined region of the complex plane, shown in Fig. 2, if and only if there exists $\tilde{P} = \tilde{P}^T$ such that

$$\tilde{P} > 0,$$
$$\begin{bmatrix} \sin\theta_i(\tilde{A}_i^T\tilde{P} + \tilde{P}\tilde{A}_i) & \cos\theta_i(\tilde{A}_i^T\tilde{P} - \tilde{P}\tilde{A}_i) \\ \cos\theta_i(\tilde{P}\tilde{A}_i - \tilde{A}_i^T\tilde{P}) & \sin\theta_i(\tilde{A}_i^T\tilde{P} + \tilde{P}\tilde{A}_i) \end{bmatrix} < 0, \quad (6)$$

where θ_i is the angle of the region shown in Fig. 2.

This particular problem is bilinear and the nonlinearities can be linearized changing the appropriate control variables Chilali and Gahinet (1996). All these changes are implicitly defined in terms of the partition of the Lyapunov matrix $\tilde{P}$ and its inverse

$$\tilde{P} = \begin{bmatrix} X & U \\ U^T & X_c \end{bmatrix}, \qquad \tilde{P}^{-1} = \begin{bmatrix} Y & V \\ V^T & Y_c \end{bmatrix}, \quad (7)$$

with X, Y, U and $V \in \Re^{n\times n}$. Since $\tilde{P}\tilde{P}^{-1} = I$,

$$UV^T = I - XY. \quad (8)$$

$\tilde{P}$ satisfies the identity $\tilde{P}\Pi_2 = \Pi_1$ where

$$\Pi_1 = \begin{bmatrix} X & I \\ U^T & 0 \end{bmatrix}, \qquad \Pi_2 = \begin{bmatrix} I & Y \\ 0 & V^T \end{bmatrix}. \quad (9)$$

Pre- and post-multiplying the first and second inequalities in (6) by the matrices

$$\Pi_2, \quad \begin{bmatrix} \Pi_2 & 0 \\ 0 & \Pi_2 \end{bmatrix}, \quad (10)$$

and their transposes, respectively, and introducing the following change of variables Chilali and Gahinet (1996)

$$\hat{C}_c = C_c V^T, \qquad \hat{B}_c = UB_c, \quad (11)$$
$$\hat{A}_c = XAY + XB\hat{C}_c + UA_cV^T + \hat{B}_cCY, \quad (12)$$

the inequalities in (6) are reduced to the LMIs described bellow

$$\begin{bmatrix} X & I \\ I & Y \end{bmatrix} > 0, \quad (13)$$

$$\begin{bmatrix} \sin\theta L_{11} & \cos\theta L_{12} \\ \cos\theta L_{12}^T & \sin\theta L_{11} \end{bmatrix} < 0, \quad (14)$$

where

$$L_{11} = \left[\begin{array}{c|c} XA + A^TX + \hat{B}_cC + C^T\hat{B}_c^T & A^T + \hat{A}_c \\ \hline A + \hat{A}_c^T & AY + YA^T + B\hat{C}_c + \hat{C}_c^TB^T \end{array}\right],$$

$$L_{12} = \left[\begin{array}{c|c} A^TX - XA + C^T\hat{B}_c^T - \hat{B}_cC & A^T - \hat{A}_c \\ \hline A - \hat{A}_c^T & YA^T - AY + \hat{C}_c^TB^T - B\hat{C}_c \end{array}\right].$$

The solution to these LMIs, together with (8), (11) and (12), can be used to calculate the controller realisation in (4). Note that one of U and V in (8) can be arbitrarily assigned, provided it is nonsingular.

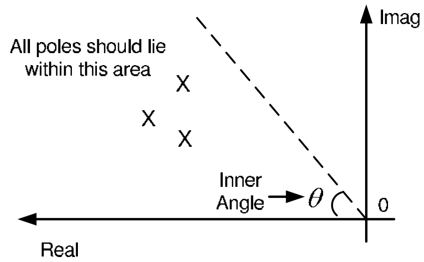

Fig. 2. All poles should be placed to the left of the predefined region with inner angle θ

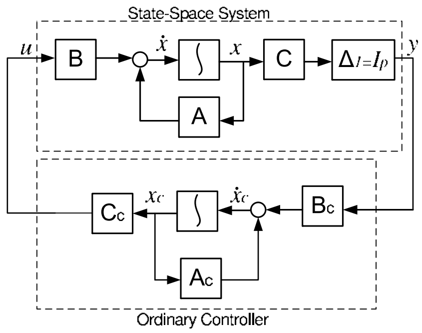

Fig. 3. Close-loop of system and ordinary controller (OC).

Finally, the closed loop of the system (1) and controller (4) is depicted in Figure 3.

2.2 Semi-active Fault-Tolerant Control

The advantage of the ordinary controller described in Section 2.1 is that is optimal when no faults occurs but its main drawback is that it lacks of fault-tolerance. Having said that, passive or reliable controllers like in Segundo Sevilla et al. (2012a) are easy to implement because its structure is fixed and are robust against a class of presumed faults but require to solve complex bilinear matrix inequalities and have limited fault-tolerant capabilities. For more details see Segundo Sevilla et al. (2013).

If precise information about the fault is available, then is possible to use these information to design an specific controller for each fault scenario and switch among the controllers accordingly. The advantage of this scheme is the combination of good performance with fault-tolerance capabilities. However, implementing such a scheme can be complex and/or challenging. As an alternative to these to extreme cases we propose a semi-active fault-tolerant control (SAFTC). In this design a unique controller is designed (similar to passive schemes) but a simple switch is incorporated into the control structure. We consider the switching control law (15)

$$K_c^i(s) \stackrel{s}{=} \left[\begin{array}{c|c} A_c^i & B_c \\ \hline C_c & 0 \end{array}\right]. \quad (15)$$

Applying the transformations (10) to (6) as before, and introducing the following change of variables

$$\hat{C}_c = C_cV^T, \qquad \hat{B}_c = UB_c,$$
$$\hat{A}_c = XAY + XB\hat{C}_c + UA_c^iV^T + \hat{B}_c\Delta_iCY, \quad (16)$$

the problem can be expressed as the solution of the LMIs (13) and (14) for all i, where

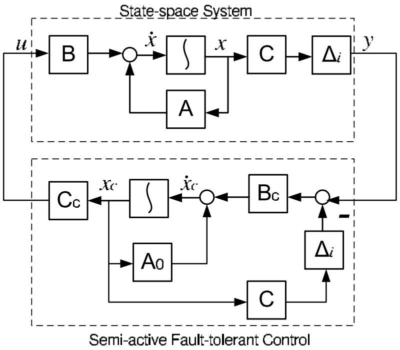

Fig. 4. Closed loop of the system and the semi-active fault-tolerant controller (SAFTC).

$$L_{11}^i = \left[\begin{array}{c|c} \begin{array}{c} XA + A^T X \\ +\hat{B}_c \Delta_i C + C^T \Delta_i^T \hat{B}_c^T \end{array} & A^T + \hat{A}_c \\ \hline A + \hat{A}_c^T & \begin{array}{c} AY + YA^T \\ +B\hat{C}_c + \hat{C}_c^T B^T \end{array} \end{array} \right],$$

$$L_{12}^i = \left[\begin{array}{c|c} \begin{array}{c} A^T X - XA \\ +C^T \Delta_i^T \hat{B}_c^T - \hat{B}_c \Delta_i C \end{array} & A^T - \hat{A}_c \\ \hline A - \hat{A}_c^T & \begin{array}{c} YA^T - AY \\ +\hat{C}_c^T B^T - B\hat{C}_c \end{array} \end{array} \right]$$

The formulation is linear. Now, an interpretation of the term $\hat{A}_c$ in (16) is given. Let $V = Y$ (recall that one of V and U are free). Solving (16) for A_c^i gives

$$A_c^i = U^{-1}\hat{A}_c Y^{-1} - U^{-1}XA - U^{-1}XBC_c - B_c\Delta_i C \quad (17)$$

Defining $A_0 = U^{-1}\hat{A}_c Y^{-1} - U^{-1}XA - U^{-1}XBC_c$ and letting $\Delta_i = diag(\delta_1, \cdots, \delta_p)$ be the diagonal matrix representing a switching matrix with $\delta_i = 0$ representing a fault and $\delta_i = 1$ representing a healthy output in the ith sensor, one can write

$$A_c^i = A_0 - B_c\Delta_i C \quad (18)$$

Figure 4 depicts the implementation of the proposed SAFTC architecture. Note that the parameters of the controller A_0, B_c and C_c are time-invariant. The time variation is restricted to the switching in $\Delta_i(t)$.

3. VALIDATION

The dynamic performance of the two different controllers described in Sections 2.1 and 2.2, respectively, is evaluated here using the reduced Nordic power system model. The energy system used for validation is shown in Figure 5. For full details of the model see Chaudhuri et al. (2010); Johansson et al. (2009); Segundo Sevilla et al. (2012b).

In nominal conditions, the Nordic system exhibits two critical inter-area modes of 0.29 and 0.55 Hz, respectively and low damping ratios as shown in Table A.1 in the appendix. Mode one (0.29 Hz) is caused by the oscillation of the generators in Finland swinging against the rest of the system while the second mode (0.55 Hz) comprises the generators of Norway, Sweden and the north of Finland swinging against the south of Scandinavia. The control objective on this work is to improve the damping of these two weakly damped modes designing a power oscillation

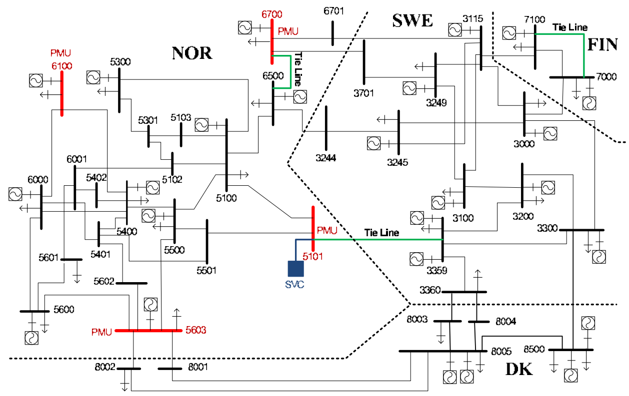

Fig. 5. Line diagram of the Nordic equivalent system.

damping controller or POD for the Flexible AC Transmission System device located in Hasle, Norway and attached to bus number 5101, as it can be observed in Figure 5.

Among all available wide-area signals from the network, 2 signals were careful selected as the most appropriated based on residue analysis (voltage angle difference between the buses 5101-7000 and 6100-700). Their residue magnitude and phase angle are highlighted in bold in Table A.2 in the appendix.

3.1 Formulation of the Control Design

In order to validate the performance of the proposed semi-active fault-tolerant controller we have compared its performance against an ordinary non fault-tolerant methodology using the reduced Nordic power system model described before. The two architectures, ordinary (OC) and semi-active fault-tolerant (SAFTC) were designed following the procedures described in Sections 2.1 and 2.2, respectively. The objective was to place the inter-area modes, described in Table A.1, in a new location of the complex plain with at least 10% of damping ratio for the case where both wide-area signals are free of fault (nominal case) following the trip of the tie-line $6700 - 6500$. In addition, the SAFTC was designed considering two more situations: the loss of the wide-area signals $5101-7000$ and $6100-7000$, respectively. For this two extra conditions, the SAFTC was designed to place the poles in a new location with at least 8% of damping ratio. Two wide-area signals were used ($p = 2$) here, which means $2^2 = 4$ possible combinations; thus $i = 1, \cdots, 4$. The different $\Delta(t)$'s represent each of the possible operations: $\Delta_1(t) = diag(1, 1)$ for the fault-free condition, $\Delta_2(t) = diag(0, 1)$ the loss of wide-are signal $5101 - 7000$, $\Delta_3(t) = diag(1, 0)$ loss of signal $6100 - 7000$ and $\Delta_4(t) = diag(0, 0)$ for the open loop case. In this work OC and SAFTC were designed for $\Delta_1(t)$ and, in addition, SAFTC was designed also for $\Delta_2(t)$ and $\Delta_3(t)$.

3.2 Nominal Case: $\Delta_1(t)$

The nominal case is depicted in Figure 6. This figure shows the power flows in the other two tie-lines (Figure 6 (a) and (b)), the voltage where the SVC is attached (Figure 6 (c)) and the output of the SVC (Figure 6 (d)). The performance using the OC is higher than one can achieve with the SAFTC as seen in the power flow $P3359-5101$ (Figure 6 (a)). On the other hand, the control effort

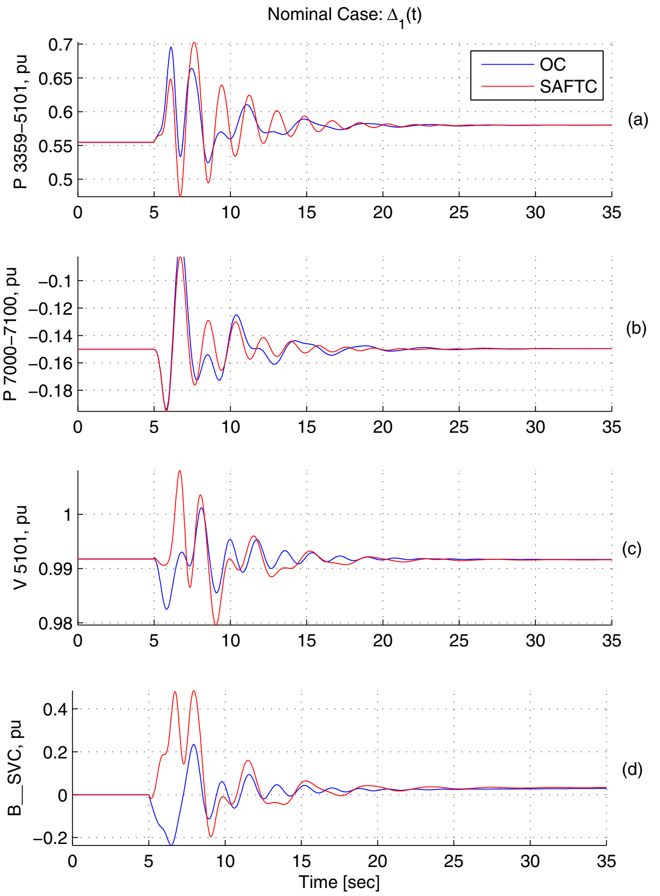

Fig. 6. Dynamic performance of the OC and SAFTC in nominal conditions; all remote signals available ($\Delta_1(t) = diag(1, 1)$).

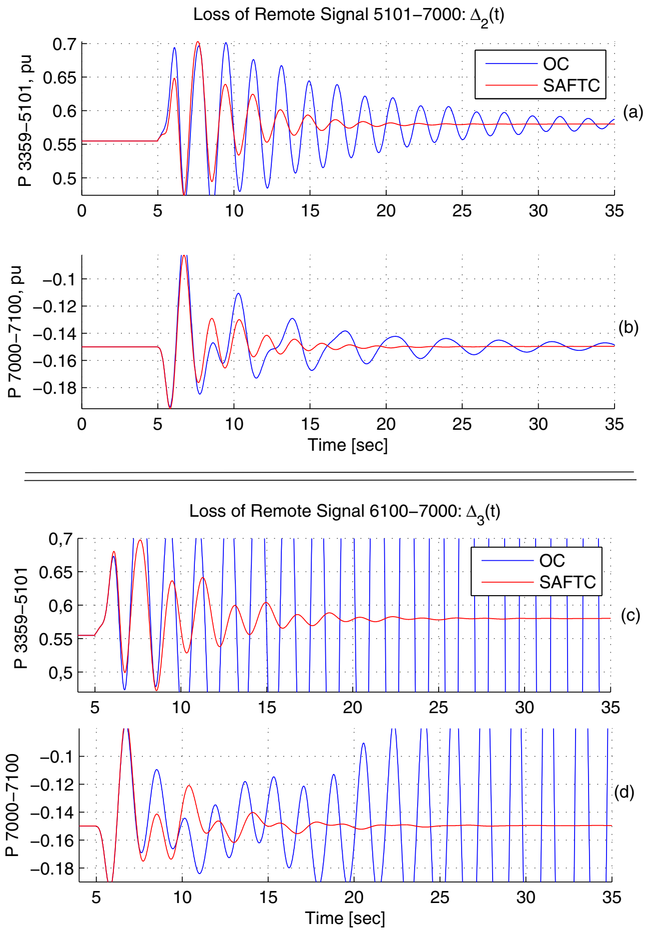

Fig. 7. Dynamic performance of the OC and SAFTC following: (a)-(b) the loss of the remote signal 1 ($\Delta_1(t) = diag(0, 1)$) and (c)-(d) the loss of the remote signal 2 ($\Delta_2(t) = diag(1, 0)$).

required by the SAFTC is higher than the OC, as seen from Figure 6 (d). The results obtained were expected, the OC provides good performance and low control effort because designed only for the optimal case (all signals available), unlike the SAFTC that was designed for different situations, the cost of including fault-tolerance is little degradation in the fault-free condition and higher control effort.

3.3 Loss of Remote Signal $5101 - 7000$*:* $\Delta_2(t)$

This operation is shown in Figure 7 (a) and (b) and corresponds to the case where the communication of the wide-are signal $5101-7000$ has bad data quality flag 0 (i.e. fault, $\delta_1 = 0$). The degradation in the performance when using the OC can be observed from the power flows $P3359-5101$ and $P7000 - 7100$, respectively (Figure 7 (a) and (b)). In this case, unlike the SAFTC the OC fails to keep the desired minimal performance, however, a stable operation of the power system is preserved.

3.4 Loss of Remote Signal $6100 - 7000$*:* $\Delta_3(t)$

This operation corresponds to the case where the communication of the wide-area signal $6100 - 7000$ fails (i.e. $\delta_2 = 0$). Under this condition, the OC cannot maintain the desired minimal performance and in addition, destabilizes the entirely power system; on the other hand, the proposed SAFTC not only ensures stability in the system but keeps the desired level of performance (damping) as shown in Figure 7 (c) and (d).

4. CONCLUSIONS

An alternative to reconfigurable fault tolerant controllers was presented in the context of electric power systems. The proposed semi-active architecture combines the advantages of both active and passive schemes. The simulation results demonstrate that an ordinary approach can degrade the performance of the system following the loss of a wide-area signal in the controller. The results confirmed the effectiveness of the semi-active approach though dynamic simulation results in the Nordic power system. The controllers presented in the document where based on linear matrix inequalities with the final objective of placing the closed loop eigenvalues in a pre-defined region of the complex plain to improve damping in the power system.

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Appendix A. TABLES

Mode No.	Frequency (Hz)	Damping ζ (%)
Mode 1	0.29	4.8
Mode 2	0.55	5.4

Table A.1. Pair of inter-area modes in the Nordic system

Signal	Mode 1		Mode 2	
	$\|R\|$	$\angle$	$\|R\|$	$\angle$
5101 − 5603	0.03	−64	0.68	−80
5101 − 7000	**2.28**	**110**	**1.55**	**83**
5101 − 7100	1.26	107	1.97	94
5603 − 6700	0.34	109	3.41	97
5603 − 7100	1.29	107	2.65	96
6100 − 7000	**2.32**	**110**	**2.44**	**88**
6700 − 7000	1.97	111	1.26	−67
7000 − 7100	1.02	−66	0.53	127

Table A.2. Residue magnitudes ($|R|$) and angles of selected voltage angles differences (selection of remote signals)