

Supervisory Control for High-Voltage Direct Current Transmission Systems [★]

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Abstract: The growth of renewable energy production is changing the future of power transmission systems. In recent years, High-Voltage Direct Current (HVDC) technologies based on Modular Multilevel Converters (MMC) are embraced by industry and academia as a solution for the efficient integration of renewable energies into electrical grids. Faster and more complex control strategies will be needed in this domain which nowadays relies heavily on human decision. This paper proposes a Discrete Event System (DES) approach to manage the control responses to deploy in an HVDC grid. Based on Discrete Event Systems (DES) modelling and Supervisory Control Theory (SCT), this paper proposes a method for synthesizing a supervisory control for HVDC systems, which focuses on local observations and limits the number of events to be communicated. The method is validated by simulation for the start-up of a point-to-point link.

Keywords: Discrete-event systems, Supervisory control, HVDC transmission systems, Decentralized control, Control system synthesis

1. INTRODUCTION

The integration of renewable energy sources to the existing electrical grids is a key issue in the domain of energy transportation. Many researchers from academia and industry propose large High-Voltage Direct Current (HVDC) networks to bring the power from remote renewable sources to load centers, given that reactive power does not have an impact on HVDC transmission links and they suffer low resistive losses (van Hertem and Ghandhari (2010), Petit et al. (2014)). Typically, the existing HVDC links use Line-Commutated Converter (LCC) or Voltage-Source Converter (VSC) technologies. Among different VSC topologies, the one based on Modular Multilevel Converter (MMC) (Saad et al. (2013)) appears to be the best solution nowadays for the development of large DC grids offering the capability to connect distant production sources to the energy consumption poles (van Hertem and Ghandhari (2010)). This type of VSC inherits the capability of easy power flow reversal and independent control of active power transfer and reactive power compensation from other VSC topologies while offering better power rating scalability and an excellent harmonic performance in comparison with traditional converters.

However, given their increasing complexity, the future generation of HVDC power systems will bring new challenges

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to the way transmission networks are controlled and operated. In Alternating Current (AC) networks, there are large synchronous generators whose rotating mass provides inertia to frequency variations. This characteristic allows to deploy slower control actions in AC systems, where the control responses take place 1 or 2 seconds after the disturbance and last up to 15 or 30 minutes (Rebours et al. (2007)). On the contrary, in HVDC systems, in absence of inertia, the transient generated by a voltage disturbance in the grid will not be compensated, and thus the control should react faster (in the order of the milliseconds). In addition, the use of MMC technologies introduces new degrees of freedom for system control. These aspects, and the wide deployment of HVDC technologies in the future will increase the complexity of grid operation, which nowadays is mainly based on decisions taken by human operators in the control center.

In this context, Discrete Event Systems (DES) modeling and the Supervisory Control Theory (SCT), developed by Ramadge and Wonham (Ramadge and Wonham (1989)), offer an adequate formal framework for the synthesis of a supervisory control system; in order to automate certain control actions and thus offer assistance to the decision making process by the human operator.

The benefits of applying DES formalism to power system related fields have been discussed in the literature. In Biswas et al. (2004), a Petri net model of a power transmission network is used for a fast analysis of the situations associated with the operation of circuit breakers after a fault in the network. However, aspects such as the

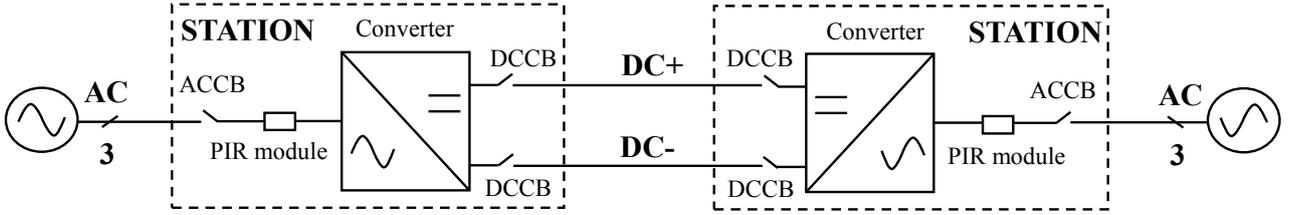


Fig. 1. Point-to-point HVDC architecture.

communication between protective relays and the coordination of circuit breakers are not treated. Zhao et al. (2006) discuss the importance of discrete event analysis and discrete supervisory control in electrical grids, but no supervisory control solution is presented. In Prosser et al. (1995) and Wen et al. (2007), a supervisor designed to guarantee system security is synthesized for line recovery in an AC power system after a fault, but ultimately the impact of the discrete control on the physical behaviour of such a critical system remains unseen, and no formal method is given that would allow a general application of the DES framework to power systems.

In this paper, the authors propose a bottom-up approach for the modelling and synthesis of a supervisory control for HVDC systems. As an HVDC grid is a system controlled in continuous-time and involving discrete commands, discrete-event modelling of each station is necessary. During the modelling stage, a comprehension of the physical behaviours is needed, as the local discrete control must guarantee that its actions will not put the system in danger. The authors propose to obtain the plant of the global grid of interconnected stations from the composition of local station models. At this point, the new physical behaviours due to the coupling of stations must be modelled. This modular approach eases the understanding of the physical system, as it decouples the global problem in local sub-problems and their interaction. Then, a supervisor for the HVDC grid is synthesized. In addition, the decentralization of the supervisory control system in order to meet the requirements imposed by the fast dynamics of the HVDC systems is presented. The mentioned method will be applied to a particular procedure of the system: the start-up.

The rest of the paper is organized as follows. First, the Finite-State Automaton (FSA) and SCT formalisms are recalled in Section 2. In Section 3, the hypothesis to be made when applying DES modelling to HVDC power systems are discussed and a case study is presented. Section 4 elaborates the process for developing a supervisory control system for HVDC grids. In addition, a method for the minimization of information to be communicated in such a control system is applied to the start-up procedure. Finally, conclusions are drawn and future work is envisioned in Section 5.

2. LANGUAGES AND AUTOMATA

A DES is a discrete-state, event-driven system which does not depend on the time and whose state evolution depends entirely on the occurrence of asynchronous discrete events (Cassandras and Lafortune (2008)). Based on the property of controllability, it is possible to divide the event set E

into two subsets, i.e. $E = E_c \cup E_{uc}$, where E_c is the set of controllable events. The occurrence of these events can be prevented by a supervisor S , as opposed to uncontrollable events in E_{uc} . The concatenation of the DES events of E forms finite strings which are represented by the infinite set E^* , derived by the operation called Kleene-closure (*). A language L is defined over an event set E as the set of all finite-length strings formed from the concatenation of events in E and is therefore a subset of E^* . A language is said to be prefix-closed if any prefix $t \in E^*$ of any string $s \in L$ is also an element of L ($L = \bar{L}$), with \bar{L} consisting of all the prefixes of all the strings in L .

Regular languages can be graphically represented by the state transition diagram of a finite automaton (e.g. Fig. 2). If the initial state of the automaton is a single state and the event $e \in E$ causes a transition from state x to a unique state such that $f(x, e) := y$, then the automaton is called deterministic. We can then define a deterministic automaton A , as a six-tuple $A = (X, E, f, \Gamma, x_0, X_m)$ where:

- X is the set of states.
- E is the finite set of events associated with A .
- $f: X \times E \rightarrow X$ is the partial transition function: $f(x, e) = y$ means that there is a transition labelled by event e from state x to state y . This function can be extended to $f: X \times E^* \rightarrow X$ in the natural way.
- $\Gamma: X \rightarrow 2^E$ is the active event function; $\Gamma(x)$ is the set of all events e for which $f(x, e)$ is defined and it is called the active event set (or feasible event set) of A at x .
- $x_0 \in X$ is the initial state.
- $X_m \subseteq X$ is the set of marked states that usually represent the completion of a task.

We can distinguish between the notions of the language generated by A and the language marked by A . The language generated by A is:

$$L(A) := \{s \in E^* : f(x_0, s) \text{ is defined}\},$$

while the language marked by A is:

$$L_m(A) := \{s \in L(A) : f(x_0, s) \in X_m\}.$$

All the strings s , starting from the initial state, whose transition function f is defined at (x_0, s) are represented by the language $L(A)$ generated by A . On the other hand, only the strings s that start from the initial state and end at a marked state ($f(x_0, s) \in X_m$) in the state transition diagram form the marked language $L_m(A)$, which is a subset of $L(A)$ and can be referred as the language recognized by the automaton. The states in the automaton A that are not accessible from x_0 by some string in

$L(A)$ are deleted, along with their attached transitions, by means of the operation $Ac(A)$ (Cassandras and Lafortune (2008)), without affecting the languages generated and marked by A . An automaton is said to be non-blocking when all its states are accessible from x_0 and co-accessible (X_m can be reached from state x), then $\overline{L_m(A)} = L(A)$.

3. MODELLING OF LOCAL SYSTEM UNDER CONTROL

Existing HVDC systems have been generally limited to point-to-point links (Fig. 1) operated by human action. The future integration of multi-terminal DC (MTDC) grids with multiple interconnected MMC stations represents a huge change in the way power systems are operated. It is thus important to correctly abstract the physical behaviour of the local subsystem in order to develop a discrete control structure capable of interacting with the controlled station that evolves in continuous time.

3.1 Modelling framework

Due to the MMC topology (Saad et al. (2013)) and the high-voltage cables nature, the HVDC grids have predominantly a capacitive behaviour. In consequence, any variation of the DC voltage can be interpreted as the charging/discharging of an equivalent grid capacitor. The HVDC systems provide a stable dynamic and thus reach a steady state. The system can be naturally abstracted into discrete models, based on this steady state behaviour. It is assumed that the discrete event occurrence is slower than the continuous system dynamic. In this way, the constraints imposed by the continuous-time dynamics will not influence the discrete-event modelling of the plant. Also, we consider that all events are observable as the state of the system can be inferred from the measurements.

3.2 Case study

Fig. 1 shows the commandable components in a converter station and their configuration for a symmetrical monopole topology (de Boeck et al. (2013)). On the DC side, the converter can be connected or disconnected from the HVDC cables (one for each pole) through the DC Circuit Breakers (DCCB). The same function is realized on the AC side by the AC Circuit Breakers (ACCB). Both the ACCB and the DCCB are associated to protective relays, which act as an interface between the circuit breakers and the rest of the system. The Modular Multilevel Converter is described in Saad et al. (2013). It consists of six equivalent controlled capacitors connected in parallel arms. Their charge and discharge in order to meet the required power transfer is controlled by high frequency commutation. When the control of the capacitors is active, the MMC is said to be deblocked. Otherwise, it stands in blocked state. The Pre-Insertion Resistors (PIR) module is active in the line when it is necessary to restrict the surge current under the safety limits. When the converter is controlled, the PIR module has no impact in the system.

At initial state, the voltage in the equivalent capacitors is zero, and so they need to be pre-charged to their rated voltage through a start-up procedure for the MMC proper operation. It is assumed in this paper that no fault occurs

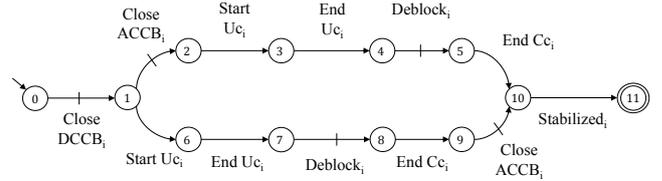


Fig. 2. Controlled station model G_i ($i \in \{1, 2\}$).

during the start-up. Among different start-up methods (Yu et al. (2013), Das et al. (2011), Li et al. (2015), Gao et al. (2014)), we consider the self-excited charging strategy, similar to the one presented in Yu et al. (2013). Since no external source is needed, this method is widely used in engineering projects (Debnath et al. (2015)). Two stages can be identified in the start-up procedure: (i) an open-loop charging phase where the MMC is uncontrolled and the capacitors control is blocked; and (ii) a closed-loop charging phase where the MMC capacitors are controlled. The MMC can have two different roles: when the MMC is connected to the supplying AC side, it is called the source converter; on the contrary, the remote converter is charged passively from the DC link and disconnected from its AC side during start-up.

Following the formalisms in Section 2, we define the model G_i ($i \in \{1, 2\}$) in Fig. 2 for the station in source role (upper string of events) and remote role (lower string of events). The transitions crossed by a line are activated by the occurrence of a controllable event, while those uncrossed are labelled by an uncontrollable event. It is therefore possible to derive from the state transition diagram in Fig. 2 the set of events $E_{G_i} := \{E_{cG_i}, E_{ucG_i}\}$, with $E_{cG_i} = (\text{Close DCCB}_i, \text{Close ACCB}_i, \text{Deblock SM}_i)$ and $E_{ucG_i} = (\text{Start Uc}_i, \text{End Uc}_i, \text{End Cc}_i, \text{Stabilized})$. The initial state is $0 \in X_{G_i}$ with X_{G_i} being the set of states. As both paths in the state transition diagram direct to the marked state 11, the language marked by G_i is non-blocking: $L(G_i) = \overline{L_m(G_i)}$. The list of transitions in G_i for each scenario, along with their physical meaning, is presented next:

- $f(0, \text{Close DCCB}_i) = 1$. In state 0, all the circuit breakers of the station are open. This transition represents the closing of the local DCCB. The closure of the DCCB is necessary for the DC cables to be charged by the source converter, or for the remote converter to be effectively charged by the DC cables.
- $f(1, \text{Close ACCB}_i) = 2$. This transition represents the connection of the source MMC to its AC side. The AC grid feeding the HVDC system is to be determined by the operator. The activation of the PIR module can also be associated to this event.
- $f(2, \text{Start Uc}_i) = 3$. After the closure of the ACCB, the current enters the HVDC link from the feeding AC grid. This current creates a voltage rise in the MMC capacitors when passing through, that upon its detection generates the uncontrollable event Start Uc_i .
- $f(1, \text{Start Uc}_i) = 6$. If there is a current circulating through the remote MMC capacitors while it stands in blocked state and that the ACCB has not been closed, the measured voltage rise means a distant station has been connected to the corresponding AC

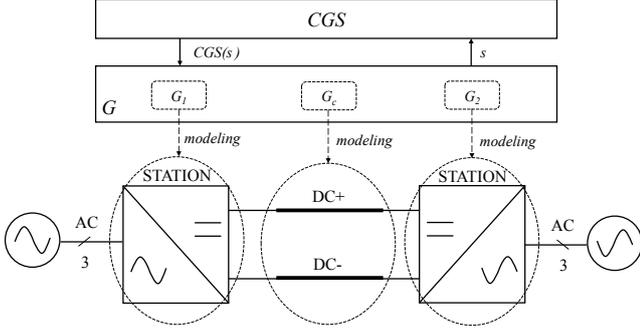


Fig. 3. Feedback loop for centralized supervisory control.

grid, and the converter is being charged from the DC link.

- $f(3, \text{End } U_{c_i}) = 4$ and $f(6, \text{End } U_{c_i}) = 7$. The End U_{c_i} event is generated when the voltage measured in the MMC capacitors reaches the steady state at the end of the open-loop energization and that a certain voltage threshold is attained. This voltage threshold is previously fixed and is different between the source and remote roles.
- $f(4, \text{Deblock } SM_i) = 5$ and $f(7, \text{Deblock } SM_i) = 8$. At the voltage level reached in steady state, the MMC capacitors can be controlled, effectively starting the closed-loop energization. The deactivation of the PIR module can also be associated to this event.
- $f(5, \text{End } C_{c_i}) = 10$ and $f(8, \text{End } C_{c_i}) = 9$. This event is generated upon arrival of the MMC capacitors voltage to the steady state at the end of the closed-loop energization. The voltage threshold is the same in both roles, and it corresponds to the rated voltage of the converter.
- $f(9, \text{Close } ACCB_i) = 10$. This transition represents the connection of the remote MMC to its AC grid, at the end of the controlled charging.
- $f(10, \text{Stabilized}_i) = 11$. The station is not fully operational until the voltages in the MMC and the DC cables are stabilized. Once the measured voltages correspond to the rated value and no large oscillations are observed, the event Stabilized is generated and the marked state 11 is reached.

The model G_i is valid for any given station, no matter if several stations are interconnected. As the connected DC grid can be approximated to a load, the addition of more stations would only change the charging slope and the voltage threshold reached at the end of the uncontrolled charging if the station was to be working as source. Similarly, the remote station would still be connected to a discharged DC link and thus its capacitors voltage would have the same appearance. Therefore, we conclude that model G_i is accurate enough for local control during start-up.

4. HVDC GRID SUPERVISOR SYNTHESIS

Following a modular approach, any grid can be constructed as the composition of several stations. Therefore, the station model G_i presented in the previous section is used for obtaining the grid plant. Then, a centralized supervisor for the global HVDC system is synthesized. Finally, the centralized supervisor is decentralized into

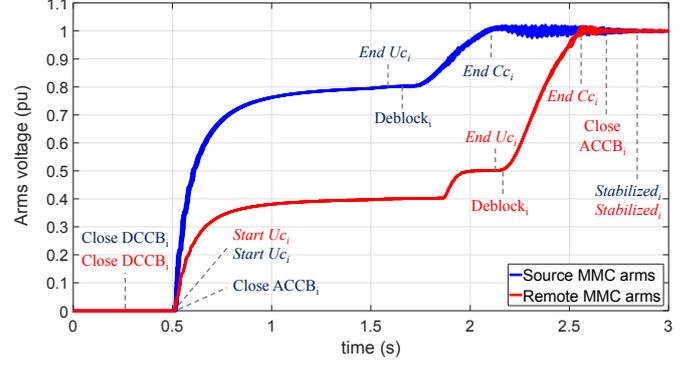


Fig. 4. MMC arms voltage appearance during start-up.

local supervisors that communicate between them, in order to respect the communication constraints imposed by the fast DC dynamics.

4.1 Method for supervisor synthesis

From the G_i model of each station, an automaton for the entire grid can be built through parallel composition. The parallel composition is an operation between automata denoted by \parallel (Cassandras and Lafortune (2008)). In the case of two automata G_1 and G_2 , it involves all the events $E_{G'} = E_{G_1} \cup E_{G_2}$. The parallel composition of G_1 and G_2 is the automaton $G' = G_1 \parallel G_2 := Ac(X_{G_1} \times X_{G_2}, E_{G_1} \cup E_{G_2}, f, \Gamma_{1\parallel 2}, (x_{0G_1}, x_{0G_2}), X_{mG_1} \times X_{mG_2})$, where $f((x_{G_1}, x_{G_2}), e) :=$

$$\begin{cases} (f_1((x_{G_1}), e), f_2((x_{G_2}), e)) & \text{if } e \in \Gamma_1(x_{G_1}) \cap \Gamma_2(x_{G_2}), \\ (f_1((x_{G_1}), e), x_{G_2}) & \text{if } e \in \Gamma_1(x_{G_1}) \setminus E_{G_2}, \\ (x_{G_1}, f_2((x_{G_2}), e)) & \text{if } e \in \Gamma_2(x_{G_2}) \setminus E_{G_1}, \\ \text{undefined} & \text{otherwise,} \end{cases}$$

and therefore $\Gamma_{1\parallel 2}(x_{G_1}, x_{G_2}) = [\Gamma_1(x_{G_1}) \cap \Gamma_2(x_{G_2})] \cup [\Gamma_1(x_{G_1}) \setminus E_{G_2}] \cup [\Gamma_2(x_{G_2}) \setminus E_{G_1}]$.

From local models G_i ($i \in \{1, n\}$), a global plant can be obtained independently of the grid size, as we can extend the parallel composition operation to n stations: $G' = G_1 \parallel G_2; G'' = G' \parallel G_3; \dots; G^{(n)} = G^{(n-1)} \parallel G_n$.

The event set of the G_i station model includes local events. Therefore, G_i is independent of the connected grid and thus valid for any given station in the case of large scale interconnection. However, even though local models are valid for local control, they do not cover all the behaviours that appear in the system when several stations are coupled. An effort has to be made to identify such physical behaviours imposed by the HVDC links. The new physical constraints in the global grid must then be modelled in the form of automaton G_c . Thus, a new global grid plant G is obtained through parallel composition $G^{(n)} \parallel G_c$.

Then, in order to obtain the desired behaviour, the set of strings of $L_m(G)$ must be restricted within the subset $K \subset L_m(G)$ according to the control specifications that we wish to enforce on the language generated by G . Conforming to the Supervisory Control Theory (SCT), these specifications are declared in the form of specification

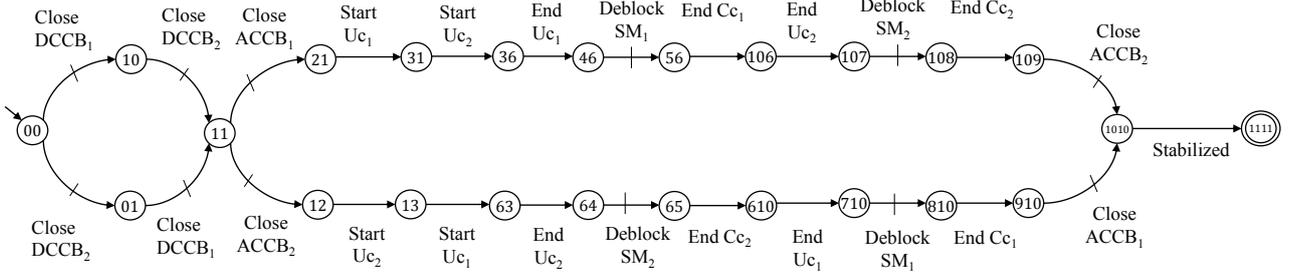


Fig. 5. Automaton R_{CGS} such that $L_m(R_{CGS}) = L_m(CG S/G)$ and $L(R_{CGS}) = L(CG S/G)$.

automata H_{G_i} . The specification H_G to be respected in the global grid is formed by the parallel composition of the different H_{G_i} . Then, we introduce a function, called Centralized Grid Supervisor (CGS) (Fig. 3), that dynamically enables or disables controllable events of $L_m(G)$ to respect the specification H_G :

$$CGS : L(G) \rightarrow 2^{E_G}. \quad (1)$$

Given the partial controllability of the system, there exists a non-blocking supervisor CGS such that $L_m(CG S/G) = K$ and $L(CG S/G) = \bar{K}$, with $K \subseteq L_m(G)$ and $K \neq \emptyset$, if and only if the controllability condition $\bar{K}E_{ucG} \cap L(G) \subseteq \bar{K}$ and the $L_m(G)$ -closure condition ($K = \bar{K} \cap L_m(G)$) are respected. If K is not controllable, the largest sublanguage of K that is controllable, with $L_m(G)$ -closure condition, can be computed.

So for $s \in L(G)$ we define $CGS(s)$ according to Cassandras and Lafortune (2008):

$$CGS(s) = [E_{uc} \cap \Gamma(f(x_0, s))] \cup \{\sigma \in E_c : s\sigma \in \bar{K}\}. \quad (2)$$

In the first term of (2), the supervisor enables after string s all uncontrollable events that are feasible in G . In the second term of (2), all the controllable events that extend s inside of K are allowed. In this way, a feasible uncontrollable event is never disabled. Then, the language marked by CGS/G is defined as follows:

$$L_m(CG S/G) := L(CG S/G) \cap L_m(G), \quad (3)$$

where $L_m(CG S/G) \subset L(G)$ is strictly contained in the language generated by G and it corresponds to the strings of the admissible procedure CGS/G .

4.2 Centralized Grid Supervisor for start-up control

We now consider the start-up management in the case of a point-to-point connection of two stations, as represented in Fig. 1. Taking the case where both converters are charged from the AC side of the source converter, the remote MMC is dependent on the source converter and the DC link as it is not connected to its AC side. Using Matlab SimPowerSystems, the evolution of the capacitors voltage in the source MMC as well as the remote MMC have been simulated. There exist multiple strings of events that could occur during start-up but, for the considered strategy, only those shown in Fig. 4 originate an acceptable voltage behaviour in the capacitors of the MMCs.

The interconnection of several stations would only increase the complexity of events coordination during start-up. It is thus necessary to synthesize a grid supervisor that coordinates the action of the local station controllers. Therefore, using the Supremica software (Miremadi et al. (2008)), we are able to generate a new plant automaton $G' = G_1 \parallel G_2$ for the entire point-to-point system, through parallel composition of the automata G_1 and G_2 of each station.

However, the language $L(G')$ contains illegal strings either because they lead to states that are physically impossible or because they violate some safety constraints that we wish to impose. The dependence in the ordering of events between the linked stations is not captured in $L(G_i)$ and it is thus necessary to define the plant G_c that models the physical constraints introduced by the DC link (Fig. 6) and completes the grid plant modelling obtained by composition of the station automata. Each string in G_c represents the order in which the MMC reaches the different steady-state voltages, depending on its role as the source or remote converter. For example, if MMC_1 is the source converter, the voltage increase in its capacitors (Start U_{c1}) will naturally be detected first in its arms and later in the remote MMC arms. Then, as MMC_2 is dependent on the HVDC grid, it will logically reach the end of the open-loop and closed-loop (End U_{c2} , End C_{c2}) charging later than the source MMC. Finally, it was necessary to distinguish the Stabilized_i event between stations in local model G_i because in a complex network all voltages might not stabilize at the same time. In our case, as there is only one line, the two stations stabilize

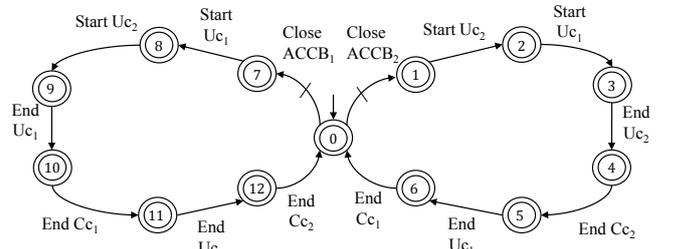


Fig. 6. Physical constraints G_c .

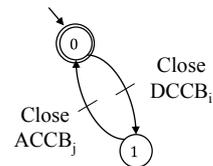


Fig. 7. Specification H_{G_i} ($i = 1, 2; j = 1, 2; i \neq j$).

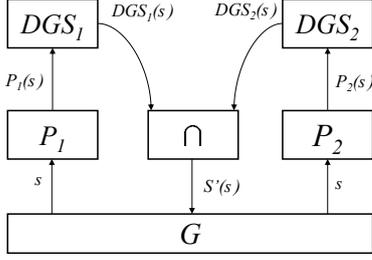


Fig. 8. Feedback loop for decentralized supervisory control.

simultaneously once both AC grids are interconnected and a power balance is established; and so Stabilized_1 and Stabilized_2 are merged into one common event Stabilized . All the states are marked as the plant models physical behaviours imposed by the HVDC link. Then the global grid model is obtained as $G' \parallel G_c$.

The specifications H_{G_i} ($i \in \{1, 2\}$) are then declared (Fig. 7). Automata H_{G_i} prevent the two stations from connecting to their respective AC grid before all the DCCBs in the HVDC link are closed, thus ensuring a safe start and a complete energization of the DC cables and both MMCs. The global specification automaton $H_G = H_{G_1} \parallel H_{G_2}$ is declared, with $E_{H_G} = (\text{Close DCCB}_1, \text{Close DCCB}_2, \text{Close ACCB}_1, \text{Close ACCB}_2)$. According to the Supervisory Control Theory (Cassandras and Lafortune (2008)), to enforce the correct alternation of events during start-up imposed by H_G with respect to the global grid plant G , we synthesize a Centralized Grid Supervisor CGS . The automaton $R_{CGS} = G \parallel H_G$ in Fig. 5 is a realization of CGS , such that $L_m(R_{CGS}) = L_m(CGSG/G)$ and $L(R_{CGS}) = L(CGSG/G)$. In our case the admissible marked language is obtained by forming $K = \bar{L}(H_G) \cap L_m(G)$ which is guaranteed to be $L_m(G)$ -closed. In H_G , all forbidden events are controllable, so the controllability condition is satisfied.

4.3 Decentralized Grid Supervisors for start-up control

A centralized supervisor has been derived for the start-up, but this architecture implies the communication of all events in E_G . Given the fast dynamics of an HVDC grid, a decentralized control (Lin and Wonham (1988), Rudie and Wonham (1992)) that enforces local control and minimizes the number of events to be transmitted needs to be considered. In this way, the events that are not critical for the tracking of the system state can be suppressed from the supervisor alphabet, ensuring a correct operation without introducing additional and undesired constraints.

The decentralized control structure is built on the joint action of two local Decentralized Grid Supervisors (DGS). Formally, given admissible supervisors DGS_1 and DGS_2 , each defined for G , we define the decentralized supervisor S' corresponding to the intersection of all DGS_i as follows: $S'(s) := DGS_1(s) \cap DGS_2(s)$ (Fig. 8). The controlled system generates $L(S'/G) = L(DGS_1/G) \cap L(DGS_2/G)$ and $L_m(S'/G) = L_m(DGS_1/G) \cap L_m(DGS_2/G)$. The strings observed in the local station suffice for stable control of the local subsystem. However, given that the specification H_G must be respected in order to obtain an admissible start-up, the events in the alphabet E_{H_G} must be communicated between DGS_1 and DGS_2 . Therefore the local

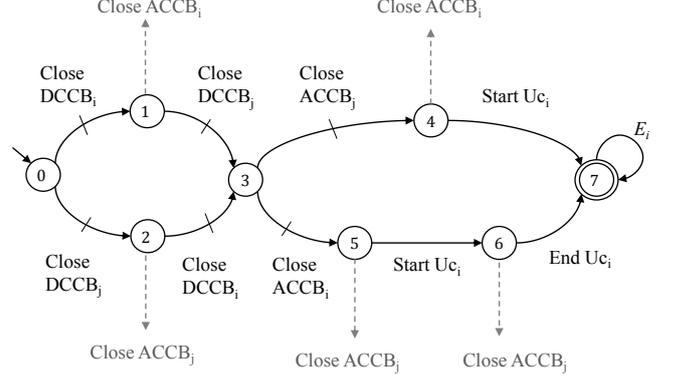


Fig. 9. Automaton $R_{DGS_{ir}}$ for supervised start-up ($i \in \{1, 2\}$; $j \in \{1, 2\}$; $i \neq j$).

alphabets $E_1 = E_{G_1} \cup E_{H_G}$ and $E_2 = E_{G_2} \cup E_{H_G}$ are determined. On these alphabets we calculate DGS_1 and DGS_2 such that $L(DGS_1) = P_1(L(CGSG/G))$ and $L_m(DGS_1) = P_1(L_m(CGSG/G))$. Similarly, $L(DGS_2) = P_2(L(CGSG/G))$ and $L_m(DGS_2) = P_2(L_m(CGSG/G))$. Projections $P_i : E_G^* \rightarrow E_i^*$ ($i \in \{1, 2\}$) take a string formed from the larger event set E_G and delete the events in it that do not belong to the smaller event set E_i :

$$\begin{aligned}
 P_i(\varepsilon) &:= \varepsilon, \\
 P_i(e) &:= \begin{cases} e & \text{if } e \in E_i, \\ \varepsilon & \text{if } e \in E_G \setminus E_i, \end{cases} \\
 P_i(se) &:= P_i(s)P_i(e) \text{ for } s \in E_G^*, e \in E_G.
 \end{aligned} \tag{4}$$

From there, the projection P_i is extended to the language $L(G) \subset E_G^*$ by simply applying it to all the strings in the language.

The synthesized supervisors are maximum permissive given that $L(DGS_1/G) \cap L(DGS_2/G) = L(CGSG/G)$ and $L_m(DGS_1/G) \cap L_m(DGS_2/G) = L_m(CGSG/G)$. If this is not the case, Overkamp and van Schuppen (2000) shows how to proceed.

In practice, the realizations R_{DGS_1} and R_{DGS_2} of DGS_1 and DGS_2 are two observers (Cassandras and Lafortune (2008)) for R_{CGS} with the partitions $E_{R_{CGS}} = E_G = E_1 \cup E_{uo1}$ and $E_{R_{CGS}} = E_G = E_2 \cup E_{uo2}$, with $E_{uo1} = E_R \setminus E_1$ and $E_{uo2} = E_R \setminus E_2$. As the control actions of DGS_1 and DGS_2 are limited to the first states, where a local event is forbidden, it is therefore possible to reduce the local supervisors (Vaz and Wonham (1986)), obtaining as a result the realizations $R_{DGS_{1r}}$ and $R_{DGS_{2r}}$ that minimize the number of states such that $L(R_{DGS_{ir}}) = L(R_{DGS_i}/G)$ and $L_m(R_{DGS_{ir}}) = L_m(R_{DGS_i}/G)$ for $i \in \{1, 2\}$. Fig. 9 presents the automaton $R_{DGS_{ir}}$, where the forbidden events, labelling the dashed transitions, are remained for better understanding.

Taking into account the communication constraints imposed by the physical system, the events to be communicated within the supervisory control system have been effectively limited while ensuring an admissible start-up. Even if there exist communication delays, grid stability is not affected by control decentralization as the voltage is in steady state when the control actions associated to the 4 controllable events included in E_{H_G} are generated.

5. CONCLUSIONS AND PERSPECTIVES

In this paper, following a bottom-up approach, we present a method for modelling and synthesizing a supervisory control for HVDC systems. First, the local controlled station is modelled for a given mode. Then, by composition of these models we are capable of constructing a global grid plant of any size. The constraints imposed by the interconnection of several stations must be specified and modelled. In this paper, the method has been validated by a simulation for the start-up of a point-to-point HVDC link. Then, a decentralized grid control which focuses on local control and limits the number of non-critical events to be communicated is synthesized.

Future work will extend the proposed method to multi-terminal grid architectures and other procedures, such as power loss compensation and post-fault restoration management, in order to develop a mode switching control structure. Also, given the characteristics of an electric power system, hybrid automata modeling (Saadi et al. (1997)) could be investigated, as continuous-time analysis techniques would give additional information about grid stability, allowing to increase performance and speed of the control system. Finally, as the supervisory control system will be required to treat synchronous I/O signals, as opposed to asynchronous events in the SCT framework, it is in scope to define a formal passage to an implementation language (PLC languages, programming code ...), based on the large number of contributions that have already treated this problematic in the literature (Vieira et al. (2017), Cantarelli and Roussel (2008)).

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