Control Structures for Multi-machine Multi-converter Systems with Upstream Coupling

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Abstract-- A multi-machine multi-converter system formalism has been proposed to describe systems composed of several electrical machines and converters. This description points out coupling elements, which have to distribute energy. Control structures have already been proposed for systems with downstream coupling. This paper is focused on control structures for systems with upstream coupling. Several solutions can be found by moving control blocks.

Index Terms-- Drives, Power conversion, Power engineering, Power system control, Power system modeling.

I. NOMENCLATURE

Abbreviations
EC: Electrical Converter
EM: Electrical Machine
ES: Electrical Source
MC: Mechanical Converter
MS: Mechanical Source
MMS: Multi-machine Multi-converter Systems

Subscripts
$X_{ec}$: variable of an electrical converter
$X_{em}$: variable of an electrical machine
$X_{es}$: variable of an electrical source
$X_{mc}$: variable of a mechanical converter
$X_{ms}$: variable of a mechanical source

$X_{est}$: estimated value of the variable $X$
$X_{mes}$: measured value of the variable $X$
$X_{ref}$: reference value of the variable $X$
$X_{w}$: weighted value of the variable $X$

II. INTRODUCTION

MULTI-machine multi-converter systems can be considered as extensions of classical drives. They are used either to extend the field of the power applications or to increase their flexibility and their operating safety. Thus, for some high power applications as the railway traction [1], the manufacturers have developed these kinds of drives for several years. These systems allow energy repartitions along the conversion chains through the coupling of power structures. But, these common physical devices induce some perturbations: over-voltages, instabilities, lower performances...

A specific formalism has been defined to make easier the multi-converter multi-machine system (MMS) analysis [2]. This study is made according to the Multi-machine Multi-converter System project of a national French GdR (Groupement de Recherche). Different coupling sections can be defined in these systems: electrical [3], magnetic [4], [5] and mechanical couplings [6]. Their analysis point out some conditions in order to ensure optimum behaviours [7]. In some applications a classical coupling can be replaced by another one in order to propose alternative solutions (as electrical differentials [8]).

For the design of the control, two kinds of coupling structures can be considered: upstream and downstream coupling. Control structures of such systems can be built thanks to an inversion principle of the power functions. For downstream coupling structure, specific energy repartition criterions are needed [9]. This paper is devoted to control structures for systems with upstream coupling elements. Other criteria have to be defined.

In the first part, the MMS formalism and the coupling devices are presented. Then, the control building of MMS is deduced by inversion rules and a general solution is suggested for upstream coupling devices. In the last section, a railway traction system is chosen to illustrate the methodology.
III. MULTI-MACHINE MULTI-CONVERTER SYSTEM

A. Mono-machine Mono-converter System

A mono-machine mono-converter system is a physical device set, which ensures an energy transfer between an electrical source (ES) and a mechanical one (MS) [2]. In a general case (Fig. 1), it is composed of three conversion structures: electrical converter (EC) electrical machine (EM) and mechanical converter (MC).

These conversion structures can own a tuning input, which adjusts their energy conversion. Power busses, called connection busses, which induce the action-reaction principle, link these devices.

This description is based on systemic and energetic considerations. All blocks have inputs and outputs according to their own causality. Moreover, the product of two variables exchanged (voltage $v$ and current $i$ for example) between two elements leads to the instantaneous power exchanged by these elements ($p = vi$ for example).

![Fig. 1. Mono-machine mono-converter system](image1)

B. Multi-machine multi-converter system

A MMS is composed of several mono-machine mono-converter systems, which share one or more power devices. Consequently, it owns coupled conversion chains, which can yield interactions (perturbations) between power structures [2].

The energy distribution is obtained by specific conversion structures. These power components are common to several conversion chains. They are called coupling structures and link an upstream device with many downstream elements, or vice versa (Fig. 2). Such structures are drawn by forms with intersections.

The electrical coupling is associated with electrical converters (EC). It corresponds to a common electrical device of several converters (power switch, capacitor...). It leads to a common electrical variable (voltage, current...). The electromagnetic coupling is associated with electric machines (EM), and the mechanical coupling with mechanical converter (MC).

![Fig. 2. Examples of coupling structures](image2)

IV. CONTROL OF UPSTREAM COUPLING DEVICES

A. Control of a Mono-machine Mono-converter System

The control structure of a mono-machine mono-converter system can be deduced from its MMS representation. Indeed the control of a system can be considered as an inversion of its modeling [9].

1) Modeling inversion

In order to impose a mechanical variable on the MS, a tuning input must be defined. The action chain is a succession of variables, which link the wished mechanical variable to the control one. On the example depicted in Fig. 3, the action chain leads to impose $x_{2-mc}$ to the mechanical source MS from the electrical source ES, through $x_{2-ec}$ and $x_{2-em}$.

The control structure has to define the adapted control variable ($x_{ec_{reg}}$ in the Fig. 3) in order to impose the wished effect ($x_{2-mc-ref}$ in the Fig. 3). Thus, control blocks are connected by reference variables, which constitute the control chain. This chain corresponds to the inversion of the action chain. In the example, the control chain has to define the $x_{ec_{reg}}$ for the electrical converter from the reference variable to impose on MS, $x_{2-mc-ref}$ through $x_{2-em-ref}$ and $x_{2-ec-ref}$.

The function of each conversion device has to be inverted by specific operations, which are controllers and perturbation rejections through measurements. In a first step, all variables are assumed to be measurable.

2) Representation of control structures

In the MMS formalism all control blocks are drawn with the same pictogram (a rhombus) because they handle only information. The continuous lines are associated to inversion operations and the dashed line to perturbation rejections. A little oval on a power variable indicates its measurement.

![Fig. 3. Control example of a mono-machine system](image3)

B. Control of an Upstream Coupling Device

1) Different coupling devices

For each conversion structure, two coupling devices can be found. An upstream device owns a single upstream power bus for several downstream elements: it has to distribute the
energy from the upstream device to the downstream elements (Fig. 4). A downstream device owns several upstream power busses for a single downstream one: it has to collect energy from several equivalent upstream sources to the downstream one (Fig. 4).

2) Control of downstream coupling

For the downstream coupling structure, the inversion is a problem because it owns several action inputs (ξt-em and ξt-mc in Fig. 4.b) which involve the evolution of the single action output (ξt-mc). Thus there are many solutions to obtain the wished action output: acting on a single action input, acting on several one’s with equal repartition…

Thus, a supplementary input for the control is necessary: it defines the wished repartition between the action inputs. It can be considered as a repartition criterion [9].

\[
x_3-ec = k_w x_{2-em-ref} + (1 - k_w) x_{3-em-ref}
\]

Fig. 4. Upstream (a) and downstream (b) coupling structures

3) Control of upstream coupling

An upstream coupling structure owns only one action input (ξt-w in Fig. 4.a) which involves the evolution of several action outputs (ξt-em and ξt-ec). The associated control block has to define the reference input to impose (ξt-em-ref) from several references induced by downstream control blocks (ξt-ec-ref and ξt-ec).

In order to solve this problem, a weighting criterion is introduced for this control block structure. It defines the part of each input reference to produce the global output reference. A weighting parameter k_w is then used. A coupling control block (or weighting block) is inserted in the control structure. An example is given in the Fig. 5, with only two downstream outputs:

\[
x_{1-es-ref} = k_w x_{2-em-ref} + (1 - k_w) x_{3-em-ref}
\]

If k_w=1 (or k_w=0), a master-slave control is obtained: only the first input reference is taken into account. In this case, the control blocks of the slave part (discontinuous lines in Fig. 5) and the coupling control block have not to be realized. Even if the control structure is so simplified, one has not to forget that an implicit master-slave criterion is used. This choice has necessarily an impact on the system behavior.

If k_w=1/2, a mean control is obtained. Of course other weighting criteria can be defined, and the weighting parameter can evolve with time. In this case, all the control blocks have to be realized.

\[
x_{w-em-mes} = k_w x_{2-em-mes} + (1 - k_w) x_{3-em-mes}
\]

Several control blocks are replaced by a weighted control block, which has to inverse an equivalent and weighted model of the real power structures.

Fig. 5. Example of an upstream coupling control

4) Moving of the control blocks

The inversion rules and coupling criteria leads to a theoretical control structure of MMS. The coupling control blocks are the key of the energy management.

In the case of upstream coupling devices, the control structure owns a lot of control blocks (except for the master-slave criterion). The practical implementation can lead to a great computing time.

In order to reduce the control operation number, the coupling control can be moved (Fig. 6). In this case, the weighting criterion is imposed to the inputs of the upstream control block. For this block, the references have to be weighted, but also the measurements:

\[
x_{w-em-ref} = k_w x_{2-em-ref} + (1 - k_w) x_{3-em-ref}
\]

V. APPLICATION TO A MMS WITH AN UPSTREAM COUPLING

A. MMS Description of the System

1) System description

The system studied is composed of a three-leg inverter supplying two induction machines for a railway traction application (Fig. 7) [10]. Both motors move the same bogie of the train. The dc voltage source is generated by a rectifier followed by an RLC filter.
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4

V

+ RLC filter

V

 Rect.

IM1

IM2

mech.

transm.

Fig. 7. Three-leg inverter for two induction motors

2) MMS Representation

In the chosen representation, the electrical source (ES) is assumed to be the generation system of the dc voltage $V_{dc}$ (Fig. 8). It is connected to the inverter, which generates an absorbed current $i_{vsi}$ (reaction variable).

The classical three-leg voltage source inverter (VSI) yields an electrical coupling, because it generates two ac three-phase voltages $v_{vsi1}$ and $v_{vsi2}$ to supply the machines. The power switches are crossed by the machine currents $i_{im}$, which are the reactions to the supply voltages of the machines.

Each induction machine (IM) produces an electromagnetic torque $T_{im}$. The mechanical part imposes a rotation speed $W_{mc}$ on the machine shafts.

The common bogie yields a mechanical coupling. It induces a linear speed of the train $v_{train}$ from the interaction between the traction forces (induced by the torques) and the resistive force $F_{res}$. It can be viewed as two mechanical converters with common devices. This drive ensures a local energy repartition, which allows a reduction of the torque produced by each motor.

The mechanical source (MS) is assumed to be the environment of the train. It yields the resistive force.

dc supply inverter machines train environment

ES

PWM

VSI

IM1

$T_{im1}$

$\Omega_{mc1}$

$v_{train}$

$V_{DC-mes}$

$\Phi_{C2}$

$\Phi_{C}$

PWM: Pulse Width Modulation

FOC: Field Oriented Control

CC: Current Controller

$\Phi_{C2}$: Flux Controller

VE: Variable Estimations

Fig. 8. MMS representation for the railway traction system

B. Global Control of the MMS

1) Theoretical control structure of the MMS studied

The global control structure is deduced from the MMS description through the inversion rules and coupling criteria. This theoretical control structure (Fig. 9) leads to a PWM (Pulse Width Modulation) block, two FOC (Field Oriented Control) blocks, a repartition block (for the torque reference) and the weighting block (for the voltage references). One can notice that the reference is generally a torque reference instead of a train reference, in railway applications.

The global traction force is generally decomposed into identical traction forces on the bogies. Thus, the mechanical coupling is solved by an equal-repartition criterion of the torque references:

$$T_{im1-ref} = T_{im2-ref} = \frac{1}{2} T_{ref}$$

The upstream electrical coupling is more restricting. It is solved by a weighting criterion:

$$v_{vsi-ref} = k_w v_{vsi1-ref} + (1-k_w) v_{vsi2-ref}$$

A masterSlave control ($k_w=0$) is a natural choice as weighting criterion. But it has been shown that this strategy leads to problems in the case of an adhesion loss on the slave wheel [10].

dc supply inverter machines train environment

IM2

$T_{im2}$

$\Omega_{mc2}$

$V_{train}$

$V_{DC-mes}$

$\Phi_{C2}$

$\Phi_{C}$

PWM: Pulse Width Modulation

FOC: Field Oriented Control

CC: Current Controller

$\Phi_{C2}$: Flux Controller

VE: Variable Estimations

Fig. 9. Theoretical control structure of the railway traction system

2) Practical control structure of the MMS studied

The most of the computing time is imposed by both FOC blocks. Indeed, they include flux observers, frame changing, flux and current controllers, and several other operations (see Fig. 9).

In order to reduce the computing time, the weighting block is moved upstream the machine controls. Thus, a weighting FOC is defined, and the weighting criterion is applied to the torque references and to the current and speed measurements:
For $k_w = 1$, only the first induction machine is controlled. The voltage references of the inverter are so defined from the first torque reference. All control blocks of the second machine can be suppressed. As the same three-phase voltages are imposed to both motors, the second one is supplied by the voltage defined for the first one. This control is called master-slave control [10].

For $k_w = 1/2$, the voltage references are defined as the mean of the voltage references of both control chains. A weighted FOC is defined through the weighting references and measurements. Thus, the control has to inverse an equivalent mean motor. This control is called mean control [10].

One can notice that, the weighting criterion has also been applied to observer structures in order to improve the flux estimation of the weighted machine [11]. Moreover, weighted behavior model control has also been applied to solve the adhesion loss by reducing the global reference torque [12].

All these control strategies have been validated by SABER simulations taking into account the dynamics of the train with a fourth order model [10].

VI. CONCLUSION

A specific formalism has been defined to describe and analyze Multi-machine Multi-converter Systems [2]. First, inversion rules have been previously suggested in order to define control structures for such systems. It has been shown that MMS with downstream coupling need repartition criteria in their control structure [9].

This paper is focused on control structures for upstream coupling device. In order to solve the coupling inversion, a weighting criterion has to define the part of each downstream control reference.

Now, with inversion rules and coupling criteria, a control structure of a MMS can be directly deduced from the MMS representation. Even if other control solutions can be found, this methodology leads quickly to one control solution.

A railway traction system [10] has been studied in order to illustrate the control structure construction. This methodology has been already successfully applied to an electric vehicle [13], a five-phase synchronous machine [14], a wind Generation system [15].

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VIII. REFERENCES


IX. BIOGRAPHIES

Alain Bouscayrol received the Ph.D. degree from INP Toulouse, France, in 1995. Since 1996, he has been engaged as assistant Professor at University of Lille (USTL), France. In L2EP (Laboratory of Electrical Engineering of Lille), his research interests include electrical machine controls and multi-machine systems. Since 1998, he has managed the Multi-machine Multi-converter Systems project of GdR-SDSE, a national research program of the French CNRS.

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