Control system of inverting substation
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Abstract
The paper analyses the main aspects to reach an adequate control system for Inverting SubStation (ISS) able to merge the necessary dynamic efficiency and the containment of some variables within the limits imposed by the plant operation.

Different control phylosophies are examined; it is shown that only some of them can be adopted to design an ISS control system and how a classical closed loop voltage control can be well suited.

For such a control system, proper specifications are fixed on the base of plant requirements. Then, on the base of the process linearized model, the controller transfer function is extracted.

Finally, numerical simulations are carried out; the results obtained are compared with those given by not linearized models of the ISS.

1 Introduction
The resort always more frequent to underground transportation systems with close headway, and the necessity to have significant electrical energy savings, are bringing to an increasing use of Inverting SubStation (ISS) supplying underground DC traction systems.

The ISSs design is a central topic that involves the analysis of different economical as well as technical aspects, (e.g. Mellitt, Goodman & Arthurton [1] and Mellitt, Mouneimne & Goodman [2]). Referring to the economical aspects, the analysis till now carried out has been mainly focused on the value of the energy saving coming from the addition of the inverters in traditional substations. Referring to the technical aspects, instead, much has been done in terms of optimal choice of the ISS location,
inverter sizing procedures and verification of the limits of current harmonics injected into the supply system. The studies until now presented have frequently dwelt upon the ISS steady-state behavior without indicating a definite structure of control; even in the more punctual cases the control has been presented with only qualitative block diagrams. Nevertheless, it is well known that a control system may largely affect the correct and optimal operation of an ISS, so its adequate choice, from a dynamic as well as static point of view, is particularly important.

The present work examines some of the aspects necessary for the definition of a control system able to furnish a good dynamic efficiency without exceeding the boundary values fixed for some variables like vehicle braking current, substation busbar voltage or pantograph voltage.

2 The ISS control

The aim traditionally assigned to the ISS control system is only of having the maximum transfer of the braking energy. Anyway, it has to be observed that the control system attends, in different way, on many factors such as: the recovered energy, the receptivity of the supply system, the power factor, the generation of harmonics, the busbar voltage, the safety of the braking and the circulating current if existing. All these elements should be tested in size and limits during the control action. Moreover it is desirable that the control itself has the ability to compensate disturbances as the temporary detachment of the pantograph or variations of the primary voltage on the AC side; doing so, it appears clearly as the design of an ISS control system is a complex task. The above mentioned concepts can be translated in mathematical terms through the following relations:

\[
\min_{i_b} \left( P_g - P_r \right) dt
\]

subject to the constraints:

- \( i_{cir}(t) < I_{cir,max} \) ;
- \( V_c < V_{c,max} \) ;
- \( V_{BB}(t) < V_{BB,max} \) ;
- \( i_o < I_{o,max} \) ;
- \( \cos \varphi(t) > \cos \varphi(t)_{max} \) ;
- \( THD < THD_{max} \) ;
- \( \frac{\pi}{2} < \alpha_{f} < \alpha_{f,\max} \) ;
- \( i_r(t_s) > I_{r,min} \geq 0 \) ;

where:

- \( P_g \) = power generated during the braking mode minus that fed to powering trains if any;
- \( P_r \) = power really recovered;
- \( T_b \) = duration of the braking mode;
- \( i_{cir} \) = circulating current;
\( v_c \) = pantograph voltage;
\( v_{BB} \) = substation busbar voltage;
\( i_o \) = vehicle braking current;
\( \cos(\phi) \) = power factor;
THD = total harmonic distortion factor;
\( \alpha_l \) = firing delay angle of the inverter thyristors;
\( i_r \) = current really recovered.

The quantities \( P_g \) and \( P_g - P_r \) depend from variables related to the particular operating condition of the system. In fact, \( P_g \) depends from the speed at which the braking starts, the number of vehicles present on the same track section and fed from the same ISS, their motoring or braking conditions, while the quantity \( P_g - P_r \) is, generally, a function of the losses due to the idle circulating and catenary current. Therefore, a substation control based on the knowledge of the above indicated variables could bring to results a little significant because neither \( P_g \) nor \( P_r \) are currently detected in substation or elsewhere.

It is then necessary to turn on philosophies of control that, even if less advanced, succeed furnishing acceptable results entirely on the base of signals available in the substation, like the busbar voltage, the current injected into the substation and the instantaneous value of the circulating current. In this way it is possible to maximize the difference between the energy entering the substation and the energy lost for circulating current, because both could be evaluated beginning from the available parameters. On this base, at least two different kind of control, both involving a change of the firing angle \( \alpha_l \) of the inverter, are possible: a constant voltage control and a variable voltage control made to follow an \textit{a priori} fixed profile. The voltage control at time-variant profile (like in the case of the adaptive control or trajectory follower controls) foresees the knowledge of either the optimal trajectories to be followed or, in a dual manner, the path of the references in relation to the requirements given in the \textit{task space}.

In a first stage of study and with analyses still lacking in the literature, it is preferable to focus on the traditional closed-loop constant voltage control and develop a series of off-line investigations that can be used to check the above indicated constraints and to make that base of knowledge necessary for moving over more sophisticated controls. The constant voltage control requires (Suzuki [3]) the choice of the inverter reference value in a range limited between the rectifier no-load voltage and the maximum insulation voltage of the catenary reduced by the maximum line voltage drop foreseen during the regenerative braking. The reference value could be fixed by parametric analyses, able to evaluate the energy really recovered and that lost for the circulating and catenary currents versus the
reference voltage. Concerning to the dynamic of the control, it is the case to note that the control system must manage the changeover between the rectifier and the inverter in such a way to realize it the most quickly as possible; particular attention must be then addressed to the value of the inverter trigger in the substation as well as to the dynamic of the process to control. Besides, the planned dynamic must be such to guarantee the bordering of the busbar voltage under the value that activates the on board rheostatic braking. Briefly, the response of the inverter closed loop control represented by the busbar voltage must have:

1) an initial value equal to the inverter triggering value;
2) a final value equal to the reference value plus or minus a prospective steady-state error;
3) a maximum value lower than the value of the rheostatic brakes starting.

The sizing of a control system needs of the ISS representation. At this aim some brief remarks on the ISS modeling follow having taken into account that an ISS representation could be easily done with linearized models; results obtained in a previous work (Gagliardi, Ippolito & Piccolo [4]) had demonstrated a good accordance with those furnished by not linearized exact models (Alternative Transient Program (ATP) and similar models).

3 Models of ISS

The ISS configurations can be basically reduced to two different circuit arrangements:

a) totally controlled AC/DC converter and line commutated inverter (fig. 1a).

b) rectifier and line commutated inverter (fig. 1b);

In both the configurations, energy saving is obtained by a line commutated inverter.

Figure 1: ISS configurations

a) with totally controlled AC/DC converter and line commutated inverter
b) with rectifier and line commutated inverter
With reference to fig.1a the analytical model of the system can be derived applying the technique of the State-Space Averaging (SSA) (Middlebrook & Cuk [5]) to the circuit of fig.2, where the presence of a single vehicle has been supposed. The presence of more vehicles nothing really adds to the generality of the model even if the formulation and the interpretation of the results, in the case of more vehicles, can be more complex.

\[
\begin{align*}
V_{I,0} & = V_d \\
V_c & = C \left( \frac{R_l + R_e}{L_l + L_e} \right) + \left( \frac{1}{L_l + L_e} \right) i_l \\
i_o & = \frac{1}{C} \left( \frac{1 - D}{R_o} - \frac{1}{L_o} \right) i_l 
\end{align*}
\]

Figure 2: Equivalent circuit of ISS with controlled bridges.

In the circuit of fig. 2 the double converter has been represented through an equivalent circuit (obtained in conditions of voltage and devices symmetries) where, furthermore, the converter is considered as operating in the continuous mode. The equivalent inductance \( L_i \) represents the internal double converter inductance, while the inductance \( L_e \) is the sum of the line (catenary-track) inductance and the on board choke inductance. The resistance \( R_i \) represents the equivalent resistance of the double converter, and it includes the effect of the voltage drop due to the commutation. The equivalent converter voltage \( V_{I,0} \) is given by the relation:

\[
V_{I,0} = \frac{3}{\pi} V_{l, \max} \cos \alpha_i
\]

where \( V_{l, \max} \) represents the peak value of the line to line voltage at the secondary windings of the transformer and \( \alpha_i \) is the firing angle of the thyristors. Choosing the pantograph voltage \( v_c \), the inverter current \( i_i \) and the vehicle braking current \( i_o \) like state variables, the dynamic equations of the system can be expressed in the state-space form as:

\[
\dot{x} = Ax + Bu
\]

\[
V_d = Cx + \frac{L_e}{L_l + L_e} V_{I,0}
\]

where the vector of the state variables \( x \), the dynamic matrix \( A \), the state matrix \( B \) and the vectors \( C \) and \( u \) are given by the following expressions:

\[
x = \begin{bmatrix} v_c \\ i_l \\ i_o \end{bmatrix}; \quad A = \begin{bmatrix} \frac{R_l + R_e}{L_l + L_e} & \frac{1}{L_l + L_e} & 0 \\ 0 & -\frac{1}{C} & 0 \\ 0 & 0 & -\frac{1}{C} \frac{1-D}{R_o} \end{bmatrix} \\
B = \begin{bmatrix} \frac{1}{L_l + L_e} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_o} \end{bmatrix}
\]
where \( C \) is the on board filter capacitor, \( E_m \) is the back e.m.f. of the motor and \( D \) is the duty ratio of the chopper.

The dynamic transfer function of the system, in the hypothesis of validity for small signals, will be:

\[
\tilde{v}_d(s) = C(sI - A^o)^{-1} \left[ (A_1 - A_2) \tilde{d}(s)x_o + Bu \right] + \frac{L_e}{L_I + L_e} \tilde{v}_{I,0}(s) \tag{5}
\]

with \( A^o = A_1D_o + A_2(1 - D_o) \), where \( A_1 \) and \( A_2 \) are the dynamic matrix of the system during the switches on state and off state respectively, and where the terms with the apex represent the small perturbations around their steady-state operating point.

With reference instead to the configuration of fig. 1b, in the hypothesis that:

(i) a single train is considered;
(ii) voltage drops on the transformer resistances due to the circulating current are negligible;
(iii) the circulating current doesn't change the commutation period, the equivalent circuit has reported in fig. 3.

\[
R = \frac{V_R - V_I}{I} \tag{6}
\]

In the circuit of fig. 3 it is possible to note the presence of the voltage generator \( V_{cir} \) that supports the average ripple current and the circulating resistance \( R_{cir} \) given by the relation:

\[
R_{cir} = \frac{\alpha L_{cir}}{3} \pi
\]

The SSA can be applied as in the previous case. The only difference is the presence of a further state variable \( i'_R \) that determines an increase in the matrices and state vector order and, therefore, computational effort and calculation time are increased too. For sake of brevity the dynamic equations of the system and the expressions of state matrices and vectors are not reported here but they may be found in Gagliardi, Ippolito & Piccolo [4].
4 The proposed control system

The linearized models presented in section 3, and the requirements of the ISS control system given in section 2, make possible the application of various techniques for the choice of the controllers. Among these one of most attractive is the feedback state control (e.g. Kim & Dewan [6]) which brings to a control system whose general architecture is shown in fig. 4.

![Feedback state control general architecture](image)

In fig. 4 it is possible to notice the presence of $n$ controllers definable through the constants $g_1, ..., g_n$, each related one by one to the state variables characterizing the process. Unfortunately, for the control of an ISS, this technique cannot be used because some of the state variables of the process are not detectable in substation, as the motor currents and the pantograph voltage.

The use of some other techniques meets problems connected to the preventive estimation of parameters that are related to the number of vehicles fed from the same substation, the identification of the operating conditions of every train and their position on the track. As a consequence, one is forced to design a control system using only the quantities in substation and so it is sufficient to have a recourse on the control system architecture shown in fig. 5.

![Control system architecture](image)

It deals with an architecture where the action of the vehicles in phase of recovery is considered as a disturbance $d$ - on the chain of direct action - evaluable trough $P_2$ transfer function of that part of the process related to the on board motor drives. In the same fig. 5 it is then possible to note the
presence of a block $P_I$ transfer function of that part of the process representative of the ISS behavior and of a unity feedback transfer function, where $P_I$ includes a time delay block representing the sample and the delay nature of the converter gating. For such a control system architecture the controller design can be made through a synthesis technique which even if of traditional employment, easily allows to obtain the necessary indications for the choice of the controllers. Once the closed loop transfer function $W(s)$ has been fixed, the controller choice follows the classical procedure which gives the following controller transfer function:

$$G_c(s) = \frac{1}{P_I(s)} \frac{W(s)}{W_d(s)};$$

where $W_d(s)$ is the transfer function that takes into account the weight of the interaction between the disturbance and the output.

5 Numerical applications

The considerations previously developed are now detailed for an underground DC traction system that uses ISS with a totally controlled AC/DC converter and a line commutated inverter. The characteristics of interest of the installation are:

- $P_{ISS} = 3$ MW
- $V_{rated} = 1500$ V
- $V_{trigger inverter} = 1600$ V
- $V_{trigger rheostatic braking} = 2000$ V

On the base of such characteristics the following specifications can be assigned to the control system:

- $V_{ref} = 1500$ V
- $V_{threshold} = 1600$ V
- Max Overshoot = 30%

Such specifications yield a closed loop transfer function $W(s)$ such as:

$$W(s) = \frac{1785.06}{s^2 + 29.62s + 1785.06}$$

and a controller transfer function $G_c(s)$ equal to:

$$G_c(s) = 1930.22 \frac{s + 11.31}{s(s + 6.19)(s + 29.62)}$$

Such a transfer function has been obtained beginning from the linearized model of the process properly simplified from the cancellation of two pairs of poles and of zeros whose contribution to the dynamic of the system can be neglected. The step response of the proposed control system of fig. 5 has reported in fig. 6.
In order to estimate the weight of the simplifications introduced in the linearized model, the implementation of a further calculation code has been made. Such a code is able to simulate, beyond the controller, also a system representative of an ISS installation with a chopper DC motor drive in braking operating conditions.

The results of such numerical experiments, carried out by the ATP program, are reported in fig. 7 in terms of busbar voltage $v_d$, vehicle braking current $i_o$ and pantograph voltage $v_c$. In particular, in fig. 7a the busbar voltage is compared with the one obtained according to the transfer function approach. The analysis of the differences between the voltages (fig. 7a), of the pantograph voltage and of the vehicle braking current kept into allowable boundaries, indicates that an ISS control system can be designed using the above mentioned procedure, based on the control specifications extracted from the ISS operation.

6 Conclusion

The paper has dealt with an ISS control system able to merge the necessary dynamic efficiency and the containment of some variables - as busbar voltage, vehicle braking current, pantograph voltage and circulating current if any - within limits imposed by the plant operation. It has been shown that among the possible control techniques, the closed loop voltage may be considered suitable for an ISS control system. Particular attention has been paid to the control system
specifications and to the controller transfer function, carried out on the base of the process linearized model. The results of the numerical simulations have shown that a good accordance between the linearized and exact numerical models of the ISS and its control system exists.

Studies are in progress either in terms of experimental tests or in the application of the robust control theory to overcome the effects of parameters or inputs variations, and to improve the efficiency of the proposed control.

References


