

ACTIVE AND REACTIVE POWER FLOW CONTROL BASED ON D-SSSC FOR LOOPED AND MESHED DISTRIBUTION GRIDS

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ABSTRACT

The deregulation of the electrical market and the emergence of small energy production units connected to the distribution grid could induce a need on the one hand, to looped or to meshed some feeders and, on other hand, to control the active and or reactive power flows [1]. Series' connected Flexible AC Transmission Systems (FACTS) devices can control active or reactive power flows in the transmission system in order to share the power between lines, to reduce line's losses or to avoid overloads for instance [2][5]. The aim of this work is to develop the control of an inverter connected in series to the distribution grid: a Distributed Static Synchronous Series Compensator (D-SSSC). A safe and reliable novel method witch allows controlling the powers flows with no need to know line's parameters is presented thanks to an automation approach.

INTRODUCTION

FACTS devices such as the Unified Power Flow Controller (UPFC), the Interline Power Flow Controller (IPFC) and the Static Series Synchronous Compensator (SSSC) can realize Power Flow Control (PFC) thanks to their series-connected converter. This is done through an adjustable phase and amplitude voltage inserted to the line in series.

The major goal of this system is then to control active and/or reactive power flow through the line, rather than the voltage injected. Thus, the desired power flow through the line should be 'translated' into the required injected voltage. Most of the theories on power exchanged with the line and those devices lead to complex and non-exploitable expressions. They cannot be used to choose controllers or even sizing them. In addition, some conclusions are contradictory as some researchers simply assumed that the active and reactive components of the injected voltage control respectively the active and reactive power flows [3], while others have found, through simulations, that the active power flow is more strongly coupled with the reactive component of the injected voltage rather than the active component [4].

First, in this paper, an approach used by control community is developed on the SSSC. This one leads to exploitable formulas that can be used to choose the appropriate controller. The non-specialists in control usually choose a Proportional and Integral (PI) controllers without looking

for others; this implies, some time, non expected behaviours of the whole system.

In the first part of this paper, the DSSSC is modelled with a perfect AC source. In the second part, the control of the DC bus voltage is studied with two control schemes which associate the control of the power flow and the control of the DC bus. In the last part, an experimental bench is used. Lab results are presented. These one are realized thanks to a real SSSC in series with a LV network, connected to dSPACE. This application translates Matlab/Simulink schematic into C code. This code is implemented on a real Digital Signal Processor (DSP) which controls the SSSC.

ACTIVE AND REACTIVE POWER CONTROL

Distributed Static Series Synchronous Compensator (D-SSSC) is a FACTS with weak active power capacity. Its structure is based on the Voltage Source Converter (VSC) where a capacitor is connected to the DC side of the device. The voltage level of the DC capacitor is regulated to its reference thanks to the active part of the voltage injected in series through the line. During this operation, the D-SSSC will act as a resistor/generator when a charge/discharge is need. The power flow through the line will be controlled thanks to the reactive part of the voltage injected. In this case the D-SSSC will act as a capacitor/inductor as the power flow through the line will be increased/decreased [5].

Amplitude current control

The first step which leads to the power flow control is the current control.

The control of the D-SSSC is synchronized with the line current thanks to a Phase Locked Loop (PLL), the voltage injected through the line will be $\pm\pi/2$ radians phase shifted. The current has to be expressed (through his amplitude) as a function of the reactive voltage injected through the line (v_{qvsc}). The approach uses in this paper lead to exploit Concordia and Park transformations [6]. Then the electrical values of the simple network in Figure 1 are expressed in the rotating frame synchronized with the current in Equation 1.

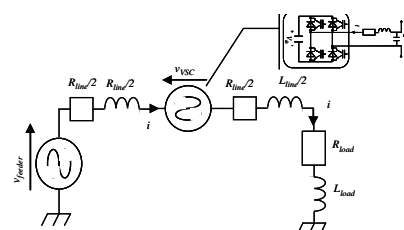


Figure 1 – Simple grid with D-SSSC

$$\frac{di_{dq}}{dt} = \left[-\left(\frac{R_{line} + R_{load}}{L_{line} + L_{load}} \right) \omega \right] \cdot i_{dq} + \frac{1}{Ll + Lch} \cdot (v_{dq_feeder} + v_{dq_VSC})$$

Equation 1

Simplifications can be done as there is no i_q value due to the synchronization of the rotation frame. This leads to the expression of the amplitude of the current as a function of v_{qVSC} and v_{q_feeder} in the Laplace domain. It can be seen that the transfer functions corresponding to v_{qVSC} , the controllable variable and to the perturbation, v_{q_feeder} , are the same. Their particularities are to be constant and equal to the inverse of the reactive part of the grid impedance (Equation 2).

$$\hat{I}(p) = i_d(p) = \frac{1}{(Ll + Lch)\omega} \cdot v_{qVSC}(p) + \frac{1}{(Ll + Lch)\omega} \cdot v_{q_feeder}(p)$$

Equation 2

The equivalent bloc diagram of the grid can be shown as the following Figure 2.

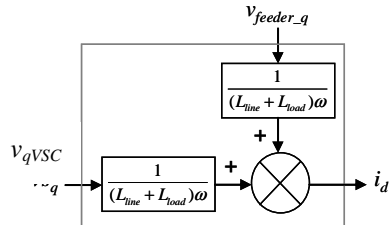


Figure 2 – Bloc diagram of the grid

The properties of the system have to be checked for a generalized looped grid index (n), see Figure 3, with m loads and where the D-SSSC is connected to the branch p.

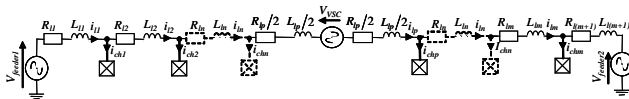


Figure 3 – Generalized meshed grid

In the same way than the simplified grid, simplifications lead to the general expression, Equation 3:

$$\hat{I} = i_{i_pd} = \frac{1}{\sum_{n=1}^{m+1} Ll_n \omega} \cdot \left(\begin{array}{l} V_{VSC_q} + V_{feeder1q} - V_{feeder2q} \\ - \sum_{n=1}^{n-1} \left(\left(\sum_{i=1}^n Rl_i + \sum_{i=1}^n Ll_i p \right) \cdot i_{load_nq} - Ll_n \omega \cdot i_{load_nd} \right) \\ + \sum_{n=p}^m \left(\left(\sum_{i=p+1}^{m+1} Rl_i + \sum_{i=p+1}^{m+1} Ll_i p \right) \cdot i_{load_nq} - Ll_n \omega \cdot i_{load_nd} \right) \end{array} \right)$$

Equation 3

Each load and each voltage feeder appears as a perturbation but the transfer function keeps his properties (Equation 4).

$$\frac{\hat{I}(p)}{V_{s_q}(p)} = T(p) = \frac{1}{\sum_{n=1}^{m+1} Ll_n \omega}$$

Equation 4

The optimal controller can then be chosen in order to have, in closed loop, the expected operation of the whole system. As the system is a fixed admittance in open loop, if the corrector used is an integrator, it will become, in closed

loop, a first order system (Equation 5).

$$C_i(p) = \frac{K_I}{p}$$

$$H(p) = \frac{1}{1 + p \cdot \left(\frac{\sum_{n=1}^{m+1} Ll_n \omega}{K_I} \right)}$$

Equation 5

First order systems present advantages: the output value will never exceed the reference value and the control is realized smoothly as there is no oscillations.

Active or Reactive Power Flow Control

The final goal of the system is to control active or reactive power. It is assumed that active and reactive power cannot be controlled at the same time as there is only one free controllable signal. So exploiting classic formulas of active and reactive power as a function of the voltage at the point of connection of the D-SSSC and the current through it, news expressions are obtained (Equation 6). These expressions are corrects as it is assumed that voltage variations are low in comparison of current ones (especially in looped or meshed grid).

$$\frac{P(p)}{V_{s_q}(p)} = \frac{3}{2} \cdot \frac{V_{max} \cdot \cos \varphi}{\sum_{n=1}^{m+1} Ll_n \omega}$$

$$\frac{Q(p)}{V_{s_q}(p)} = \frac{3}{2} \cdot \frac{V_{max} \cdot \sin \varphi}{\sum_{n=1}^{m+1} Ll_n \omega}$$

Equation 6

These expressions will be opposed to experimental results, (last part of the paper).

DC BUS CONTROL

Once, the rules of the power flow control have been set. The control of the DC bus device has to be done. Two methods are then proposed in the next section.

Parallel control scheme

The first control of the DC bus voltage is realized by direct action on the active part of the injected voltage. The voltage injected through the line is an image of the modulating β (or u when discretized) as the VSC can be seen as an amplification of β varying between -1 and 1 (the signal to amplify) by the gain V_{dc} [6]. The first step is to express the current through the DC bus as a function of the active part of the modulator and the line current. See Equation 7.

$$i_{dc} = i \cdot \beta_d$$

$$\langle i_{dc} \rangle = \langle i \cdot u_d \rangle$$

$$\langle i_{dc} \rangle = \frac{I_{max} \cdot u_{d_max}}{2}$$

Equation 7

This current flows through the DC bus which is modelled by a resistor (R_c) in parallel with a capacitor (C). The evolution of the voltage can be obtained (Equation 8).

$$\frac{v_{dc}(p)}{u_{d_max}(p)} = T(p) = \frac{I_{max} \cdot R_c}{2} \cdot \frac{1}{1 + R_c \cdot C \cdot p}$$

Equation 8

Parallel control scheme

In Figure 8, the control of the DC bus to 400V can be observed (yellow: amplitude of the line current (A); blue: line current in phase 1 (A); green: voltage of the DC bus (V) and pink: voltage injected in series through the line (V)).

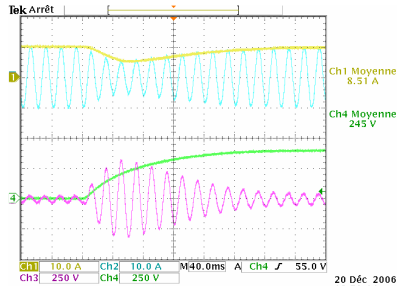


Figure 8 – Parallel control scheme – Control of the DC bus to 400V

The characteristic response of a first order system to a step reference is observed. The system behaves like a resistor as it absorbs energy. This is why there is a diminution of the line current.

In Figure 9 the control of the line amplitude current to 5A is presented. The characteristic response of a first order system can still be observed. The SSSC behave essentially as an inductor (see the phase shifting between the voltage injected and the line current).

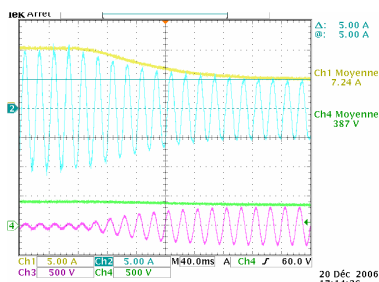


Figure 9 – Parallel control scheme – Control of the line current to 5A

Inner loop control scheme

In Figure 10, the inner loop control is presented where the line is compensated in order to increase the line current. It goes from 9A, where the system behaves like an inductor, to 11A where it acts as a capacitor. The DC bus voltage level is adapted in accordance to the series voltage needed for the compensation.

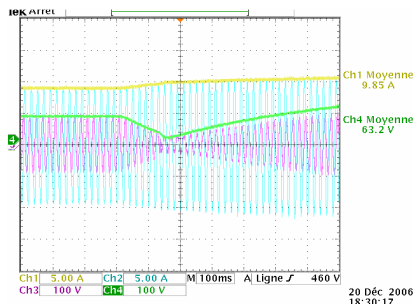


Figure 10 – Inner loop control scheme – Control of line current to 11A

In Figure 11, the reactive power flow control is presented. It is decrease (blue) to 800Var following a first order step

response as the active power flow naturally increases (yellow in Watt). The low evolution of the voltage in each part of the SSSC (pink and green in V) can be seen.

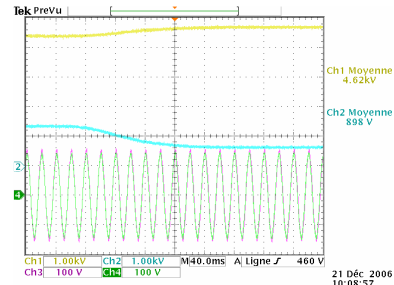


Figure 11 – Inner loop control scheme – Reactive Power Flow control to 700Var

CONCLUSION

In this paper, a novel method to realize power flow control thanks to a SSSC has been presented. This is a simple and generic method. Inner loop control scheme is preferred to parallel control as there is less harmonics and losses generation. The viability of the control has been experimentally checks and gives good results. SSSC for PFC seems to be interesting in looped / meshed network but the protecting scheme as to be revised because of the increase of short circuit current. The SSSC could be used to decrease the short circuit current in order to be still compliant with actual protection scheme.

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