Using Hysteresis Band Method for the Control of Three-Phase STATCOM Connected to a Transport Network

Ndjiya Ngasop, Asnang David, and Haman-Djalo

Abstract—The transit of reactive power through electrical transmission lines due to inductive loads creates instability problems on electrical networks. Indeed, industrialization and/or population growth are increasing these inductive loads exponentially and making transport networks more vulnerable to problems of voltage instability. Power system operators are constantly seeking for effective solutions to these problems. The STATCOM (STATic COMpensator) is one of the devices in the Flexible Alternating Current Transmission System (FACTS) family used for reactive energy compensation. It generally offers better characteristics compared to other FACTS devices and to conventional reactive power compensation devices. The aim of this paper is to apply the STATCOM controlled by the hysteresis band control method for maintaining voltage in electrical transport network. Taking into account the effects of a transport line, the characteristics of the system with STATCOM have shown encouraging results compared to the system without STATCOM.

Index Terms—FACTS, Hysteresis Band Current Control, STATCOM, Transport Network.

I. INTRODUCTION

The STATic COMpensator (STATCOM) is a regulating device based on power electronics which consists of a Voltage Source Converter (VSC) and is connected in parallel to the electrical distribution or transport networks with alternating current [1]. The voltage source is created from a DC capacitor and the STATCOM can exchange reactive power with the network [1]-[8]. Compared to conventional compensation devices such as capacitor banks, synchronous machines and inductors, the STATCOM has proven its worth and the latter gives much better results [2], [7]. However, for STATCOM to perform its role effectively, it needs a very appropriate control method. Several methods can be encountered in literature. That of hysteresis seems to have several advantages, namely: simplicity, robustness, etc. In addition, this method can be applied for non-linear loads (partial knowledge or ignorance of load model) [1], [2].

This work is divided into six sections. Section I is devoted to the introduction. Section II presents the mathematical model and topology of STATCOM studied. Section III describes the principle of the hysteresis band current control method. The description of the system studied and the discussion of results are presented in the fourth and fifth section respectively. And finally section VI concludes the paper.

II. STATCOM MODEL IN ABC AND DQ FRAMES

The mathematical model of STATCOM proposed in literature are based on the transformation of abc to qd frame [1], [9]. The STATCOM topology studied in this paper is a 6-pulses three-branch converter based on Insulated Gate Bipolar Transistor (IGBT) switches as shown in the basic diagram in Fig. 1.

![Fig. 1. Basic STATCOM circuit connected to the network [1].](image1)

The STATCOM can be modeled as an AC voltage source where the magnitude, phase and frequency of the output voltage can be controlled [1].

![Fig. 2. Three-phase equivalent circuit of STATCOM.](image2)

The equivalent STATCOM diagram in three-phase frame is shown in Fig. 2. From this figure, the equations defining the STATCOM can be written as follows:

By applying Kirchhoff's laws on the alternating side, we have:

\[
[v'] = \frac{L_j}{\omega} \frac{d}{dt} [i'] + R [i'] + [v']
\]

(1)

\[
[i_c] = \frac{1}{\omega C} \frac{dv_c}{dt} + \frac{v_c}{R_c}
\]

(2)

To establish the connection between the AC and DC sides, we can consider the instantaneous power of the VSC, such that the instantaneous power on the DC side of the converter is always equal to that on the AC side:
\[ v_{dc}'v_{dc}'' = v_{ja}'v_{ja}'' + v_{jb}'v_{jb}'' + v_{jc}'v_{jc}'' \]  \hspace{1cm} (3)

The above relationship can be rewritten using the switching functions \((S_a, S_b, S_c)\) signals, describing the generation of AC voltages from DC voltage.

\[
\begin{bmatrix}
  v_{ja}' \\
  v_{jb}' \\
  v_{jc}'
\end{bmatrix} = \begin{bmatrix}
  S_a \\
  S_b \\
  S_c
\end{bmatrix} \begin{bmatrix}
  v_{dc}' \\
  v_{dc}''
\end{bmatrix}
\]  \hspace{1cm} (4)

where \(k_i\) is a factor that depends on the type of converter. It allows the different converter topologies with AC/DC relations to be taken into account.

From (3) and (4), we obtain:

\[ i_{dc}' = k_i(S_a'j_a' + S_b'j_b' + S_c'j_c') \]  \hspace{1cm} (5)

Substituting (5) in (2), we obtain a description of DC side given by (6):

\[
\frac{dv_{dc}'}{dt} = k_\omega C\left[S_a'j_a' + S_b'j_b' + S_c'j_c'\right] - \frac{\omega C}{R_c} v_{dc}'
\]  \hspace{1cm} (6)

STATCOM's complete three-phase equation system (DC and AC sides) is as follows:

\[
\begin{bmatrix}
  i_a' \\
  i_b' \\
  i_c'
\end{bmatrix} = \begin{bmatrix}
  -R_\omega S_a/L_1 & 0 & 0 & -k_\omega S_b/L_1 \\
  0 & -R_\omega S_a/L_1 & 0 & -k_\omega S_c/L_1 \\
  0 & 0 & -R_\omega S_a/L_1 & -k_\omega S_c/L_1
\end{bmatrix} + \frac{\omega C}{R_c} \begin{bmatrix}
  v_{dc}' \\
  v_{dc}''
\end{bmatrix}
\]  \hspace{1cm} (7)

Applying the Clarke and Park transformations to (7), we can obtain (8), describing the complete mathematical model of the STATCOM in the synchronizing rotating frame (dq).

\[
\begin{bmatrix}
  \frac{d}{dt} i_{d}' \\
  \frac{d}{dt} i_{q}' \\
  \frac{d}{dt} i_{dc}'
\end{bmatrix} = \begin{bmatrix}
  -R_\omega S_a/L_1 & 0 & -k_\omega S_b/L_1 \\
  0 & -R_\omega S_a/L_1 & -k_\omega S_c/L_1 \\
  3k_\omega C_d S_a/2 & 3k_\omega C_d S_b/2 & -k_\omega C_d/L_1
\end{bmatrix} \begin{bmatrix}
  i_{d}' \\
  i_{q}' \\
  i_{dc}'
\end{bmatrix} + \frac{\omega C}{R_c} \begin{bmatrix}
  v_{dc}' \\
  v_{dc}'' \\
  0
\end{bmatrix}
\]  \hspace{1cm} (8)

III. STATCOM CONTROL

The control of the STATCOM consists of first generating reference signals from the DC side voltage and the source and load voltages and currents. These reference signals are sent to the controller which will generate pulses to control the opening and closing in a correct way for reactive power compensation and reduction of harmonics in power system [12]-[17].

A. Reference Signals Generation

There are many theories available for the generation of reference source currents in literature including: instantaneous reactive power theory (pq theory), synchronous reference frame (SRF) theory, controller based on proportional-integral (PI) regulators, etc. Among the different control techniques applied to three-phase compensators, the SRF-based technique is suitable for different STATCOM topologies [13], [15], [16]. This theory is simple and has comparatively better performance under various operating conditions. The theory we have adopted in this paper is the Synchronous Reference Frame (SRF) theory simplified as shown in Fig. 3 [2].

This system is designed so that when the load setpoints change resulting the variation of the reactive power, the voltage also changes (increases or decreases).

![Diagram of STATCOM connected to the grid using hysteresis band current controller based simplified SRF theory](image-url)

**Fig. 3:** STATCOM connected to the grid using hysteresis band current controller based simplified SRF theory

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This voltage is detected by the voltage sensor and is compared with the reference voltage and generates an error signal which, when passed through the PI controller, produces a reference quadrature axis current ($I_q^*\)).

Similarly, DC link voltage capacitor is compared with the voltage value that is supposed to remain constant and generates an error signal that is sent to the PI controller, produces a direct reference axis current ($I_d^*\)$. The reference currents direct and quadrature axes undergo an inverse Park transformation producing reference abc phase currents ($I_{abc}^*\)).

**B. Hysteresis Band Current Controller**

It is important to remember that classical control techniques based on Pulse Width Modulation (PWM) such as Sine Pulse Width Modulation (SPWM), Space Vector Modulation (SVM), etc. require the exact knowledge of the load model which is the main factor for synthesis PI controllers that have to generate references of the voltages applied to VSC. This gives them a constant switching frequency. So, this resulting very regular voltage and current waveforms.

In case the load model is not specified, the above mentioned linear PWM control techniques give poor performance. For this reason, non-linear hysteresis controllers are recommended. The advantages of the hysteresis controller are simplicity, robustness and fast response time [14]. Moreover, they can be applied even when the load model is not specified. The principle of this method described in Fig. 4.

In the hysteresis regulator, as shown in Fig. 4, if the error between the actual current and the reference current is greater than the preset value HB (called the hysteresis band), then the state of the switch is changed to reduce the error. The descriptive algorithm is given as follows:

- If $i^* - i \leq -HB$, $S_2 = ON$, $S_1=OFF$ ($v_0=-0.5\times V_{dc}$ implying a current decrease in the band)
- If $i^* - i \geq HB$, $S_1 = ON$, $S_2=OFF$ ($v_0=0.5\times V_{dc}$ implying a current increase in the band).

**IV. SYSTEM DESCRIPTION**

The VSC-STATCOM is applied to a transport line of the Cameroon North Interconnected Network (NIN).

A calculation of the power flow on the network using Newton-Raphson method showed that the transmission line connecting Lagdo-Ngoundere has lower voltage and higher active and reactive losses. The Newton-Raphson method is the most important method for the resolution of computation of power flow particularly for the complex powers flow network. It is based on Taylor series (sequential linearization) and partial derivative [10], [11].

The flow diagram of the Newton-Raphson method used on the NIN 14-bus network is presented in Fig. 5.

The block scheme obtained with SIMULINK is shown in Fig. 6 below.

The parameters of system under study are given in Table I.

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**Table I: Studied System Parameters**

| Voltage source | 110 kV |
|----------------|--------|
| Line length    | 252 km |
| Active load    | 25 MW  |
| Reactive load  | 23 MVAr|
| Fundamental frequency | 50 Hz |

**Fig. 5. Flowchart of the Newton-Raphson based load flow calculation.**
The simulation conditions are as follows:

**CASE 1**: system without STATCOM: $P = 25$ MW, $Q = 17$ MVAR

This case represents the network with characteristics equal to the case of the power flow (ideal case). This will allow us to visualize the waveforms of powers and voltages under the best operating conditions.

**CASE 2**: system without STATCOM: $P = 25$ MW, $Q = 23$ MVAR

Here, the reactive power has increased so that there is a voltage drop exceeding the allowable limit that is 10% of the nominal value. The curves are observing without the contribution of STATCOM.

**CASE 3**: system with STATCOM: $P = 25$ MW, $Q = 23$ MVAR

For this case, the same characteristics as for case 2 introduced. However, we observe the results when the STATCOM connected to the network and we compare them with the results obtained without STATCOM.

The results obtained shown in the Fig. 7 to Fig. 16 below.
Figure 7 shows the reactive power curves provided by source for the 3 operating cases. The green color curve (lower curve) is that of the reactive power when the system is under a load of 17 MVAr (CASE 1). Under these conditions, the reactive power supplied by source is of order of 0.5 MVAr. When the reactive power of the load has been increased to 23 MVAr, we observe a remarkable increase in the reactive power at source to 5 MVAr (red curve in middle). And when the STATCOM is connected, the reactive power provided by source is greatly reduced (1.3 MVAr), proving that the STATCOM provides the largest part. This is confirmed by Fig. 8, which represents the reactive power at the STATCOM.

We note from Fig. 8 that the amount of reactive power removed at source was provided by STATCOM. Indeed, if we sum the reactive power supplied by source when the STATCOM is connected (top curve in blue) and the reactive power coming out of STATCOM (curve of Fig. 8), we find exactly the power reactive provided by source when the STATCOM is not connected to the network.

From Fig. 9, we can see that the STATCOM consumes an amount of active power up to 2.5 kW. This result disagrees with that obtained by [2], when the authors used the same control method on 400 V test network. We can justify this consumption by the fact that, we have to compensate a transmission network, the powers involved are of the order of mega; and thus the STATCOM consumes more active power to compensate for its losses in the DC circuit, given its topology.

However, in Fig. 10 and 11, we can see that the STATCOM has a beneficial effect on the transmitted active power that is well related to the results found by [2].

Finally, we visualize the voltages in the three cases of previous systems.

From Fig. 12 to Fig. 16, the load voltages are shown for different system operation cases.

In the best case (CASE 1), the voltage is 0.92 pu (Fig. 12). This is understandable as this value is within the voltage limit of 10%. In CASE 2, when the load consuming 23 MVAr, the voltage drops to 0.86 pu (Fig. 13) thus veiling...
the voltage limit. With this value, the system is unstable. However, when the STATCOM is connected to the network, the voltage value is raised to 0.91 pu (Fig. 14), thus approaching the normal mode, and this value is within the limit of the voltage proving that the system becomes stable again with the STATCOM. In Fig. 15, a comparison between the load voltage without and with STATCOM are shown for phase A. It is easy to see that the load voltage magnitude when the STATCOM connected to the network is much greater than without the STATCOM.

Fig. 16 shows the actual and reference current waveforms. It can also see that, the actual current follows the reference current in the hysteresis band. This shows that the chosen control method is successful.

VI. CONCLUSION

This work revealed the effectiveness of STATCOM device in a transport network. The system under study is a 14-bus network of NIN Cameroon. The Newton-Raphson power flow study enabled us to identify the line of Lagdo-Ngaoundere about 252 km as the one with the greatest power losses. For the STATCOM control, we used the hysteresis band current control method based on the synchronous reference theory. This method, unlike the others (SPWM, SVM, etc.) has the advantages of simplicity, robustness and fast response times. The results obtained reveal that the STATCOM compensates for the reactive energy in the network and maintains the voltage at an acceptable magnitude. A comparative study was carried out on the load voltages of systems without and with STATCOM. The voltage was 0.86 pu for the system without STATCOM was increased to 0.91 pu when the STATCOM was connected; which is approaching the case of normal mode operation (0.92 pu). Our results also revealed that the STATCOM can increase the transmittable active power in an electrical network. We can therefore conclude that the STATCOM can be used effectively in a transmission network provided that the control technique of STATCOM is employed and by choosing a suitable STATCOM topology. We can consider further techniques such as adaptive fuzzy hysteresis and multi-level topologies to further reduce the active power consumed by the STATCOM.

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