Modelling Static Watt-Var Compensators using ATP

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Abstract **The paper deals with some of the main issues the author has met when simulating the power electronics device called Static Watt-VAR Compensator (SWVC). Some of them are:**

- **problems relating to the choice of timestep, that has to be very small in comparison to the circuit time constants, due to the Pulse-Width Modulation (PWM) converter;**
- **challenges posed by the complexity of control, in particular, techniques to use a discrete-time multi-input-multi output (MIMO) controller**
- **modelling of lead-acid batteries.**

The paper presents also some results of simulations on simple network of the behaviour of this kind of devices, both in the so called *parallel* and *islanded* operations, showing the great flexibility of these devices, whose usefulness in power systems has already been demonstrated by many papers.

The program used for all the simulations discussed in this paper is the well known simulation program ATP [1]

I. INTRODUCTION

Power electronic devices allow very flexible and fast manipulation of the electric quantities of an electrical system.

Their capabilities are increasingly considered for use in power systems to perform a large variety of services.

One of the more flexible devices proposed is the device called Static Watt-Var Compensator (SWVC), or Battery Storage Plant (BSP).

Static Watt-Var Compensators are able to exchange with an AC node active and reactive powers with any combination of signs.

Their use is more and more widespread in power system because of their ability to perform a large variety of services: load levelling, peak shaving, emergency, power factor compensation / voltage regulation, etc. [2, 3, 4].

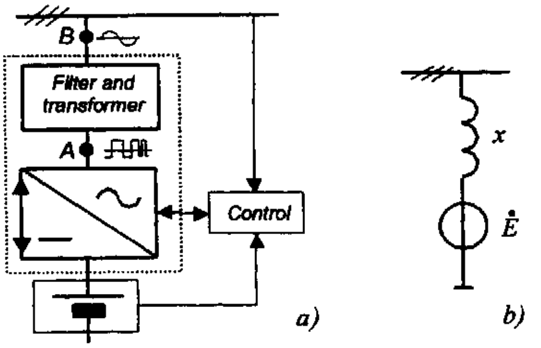

Fig. 1: Principle scheme and AC equivalent of an SWVC.

A schematic description of the device is reported in fig. 1. The main parts of the device are:

- An energy storage, normally constituted by an electrochemical battery, often of the lead-acid type
- a power conditioner (dotted box in figure) that converts the electric power from DC to AC (at the needed voltage level) and vice-versa
- the control that implements the different functions that, for every specific installation, the device is required to perform.

The simulation of this device poses to the engineer several challenges, mainly:

- simulation of the non-linear, dynamic behaviour of the battery
- simulation of the several control functions of the device;
- simulation of the AC-DC bi-directional converter shown in figure.

This paper shows how these problems can be solved, and reports some sample simulations that show the device effectiveness on one hand, and the ability of ATP simulating it satisfactorily, using the proposed techniques.

II. THE STATIC WATT-VAR COMPENSATOR

The Static Watt-Var Compensator (SWVC) has been presented in the Introduction.

At the industrial frequency it can be modelled by the simple equivalent shown in fig. 1 *b)*.

It can be easily seen that this model is equal to a simplified model of a synchronous machine; the main differences are that the reactance x is much lower (values of 10-20% can be envisaged) and amplitude and phase of E can be varied much faster. These two differences make the SWVC controllability much greater than that of a synchronous machine. Another noticeable difference resides in the fact that since the active power delivered to the network is drawn from a limited-capacity battery storage, the usage of this component requires a suitable management of the energy level of this storage, and the control strategies are to be defined taking into account this constraint.

III. LEAD-ACID BATTERY MODELLING

An electrochemical battery can be simulated by models of different complexities, depending on the degree of precision required and on the application of the battery in the power systems.

In general, the battery can be analysed taking as reference an electric network of the type shown in fig. 2 (cf. [7]). However, the involved time constants $\tau_1=R_1C_1$ and

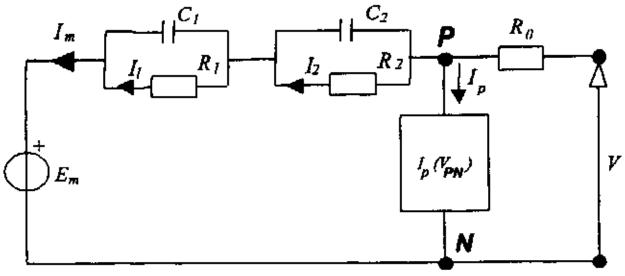

Fig. 2: Electric network equivalent to a lead-acid battery.

$\tau_2 = R_2C_2$ are in the order of minutes or even hours, and the related dynamics can therefore be neglected when analysing fractions of seconds with an electro-magnetic transients program.

The shunt branch between nodes ***P-N*** models parasitic reactions occurring the end of a charge process and therefore it draws a negligible current during discharge or during charge and the battery is not nearly completely full.

As a consequence of these considerations, a battery model adequate for simulation of a SWVC is the simple model reported in fig. 3, while it is to be remembered that the circuit parameters (f.e.m. E_{eq}, resistance R_{eq}) depend not negligibly on the battery state-of-charge SOC, and temperature θ. The functional relations relating these quantities can be derived from [7].

IV. PWM INVERTER MODELLING

The most widely used technique to control the converter shown in fig. 1 is the Pulse Width Modulation, or PWM. In this paper the sine-triangle technique is used.

The pulse generation by means of comparing sine and triangle waves is very easily performed in ATP using MODELS.

The main issue that the author has met in simulating the PWM converter was the choice of the timestep.

In fact, differently from other cases, the timestep has to be correlated more with the precision of the intersection times between carrier and modulating waves (fig. 4) than with the time constants of the linear circuit elements. Several tests have shown that this precision is to be very strong in order to avoid numerical consequences on the results.

In fig. 5, for example, the simulated condition of "stand-by", i.e. the condition in which the SWVC, connected in parallel with an infinite-power networks, is controlled so that active and reactive power exchanges are both zero. Some of the characteristics of the considered SWVC are reported in Appendix. The variable shown is the instantaneous active power exchanged by the device.

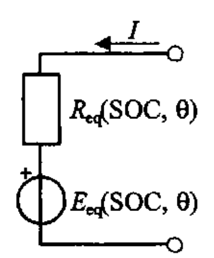

Fig. 3: Simplified battery model

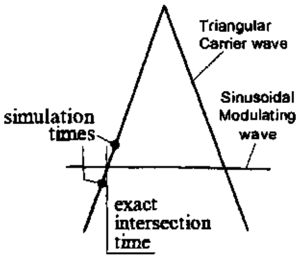

Fig. 4: Sine-triangle intersection of a PWM, and simulation timestep

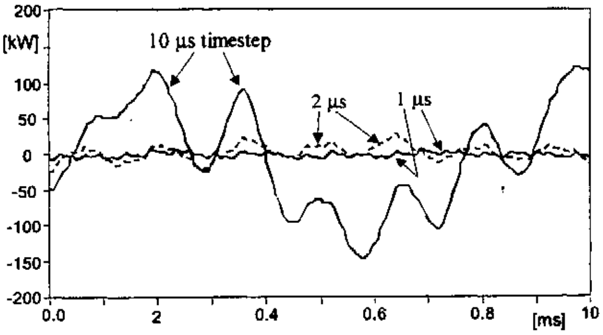

Fig. 5: Comparison of different timesteps during simulation of "Stand-By" operation.

It can easily be seen that

- there are very strong differences in the results obtainable with 2 and 10 microseconds
- the results that can be obtained using 1 or 2 microseconds are substantially similar, a stronger "jitter" can be seen on the curve obtained with a timestep of 2 µs.

Therefore a timestep as small as 1-2 microseconds is required in this simulation; this implies very long computing times.

This can be seen as a consequence of the fact that it is not possible to impose simulating times in corresponding to the opening/closing of switches, and therefore the fixed program timestep has to be reduced so that it allows the identification of these times with sufficient precision.

As a consequence of this it appears as highly desirable to have in the simulation program the possibility to force additional simulation times (times in which the variables are computed) in correspondence to the switching times. In case of ATP this could be implemented as a new MODELS command, for instance.

This requirement is not strictly related to the particular system simulated in this paper: it is also advisable in all cases in which power electronics containing semiconductor devices that can be turned on and off by control signals.

V. P-Q CONTROL

It has been stated that Static Watt-Var Compensators are able to exchange with an AC node active and reactive powers with any combination of signs. In particular, they have a capability region that by large can be assumed as a circle in the P-Q plane.

The two variables P and Q can be independently controlled acting on the two input variables of the PWM controller (fig. 6):

- amplitude modulation ratio m (ratio of the amplitude of the modulating sine wave to the amplitude of the carrier triangular wave)
- phase-angle β of the modulating sine wave.

To define the controller, some modelling of the SWVC must be considered.

As well known, the fundamental-frequency component

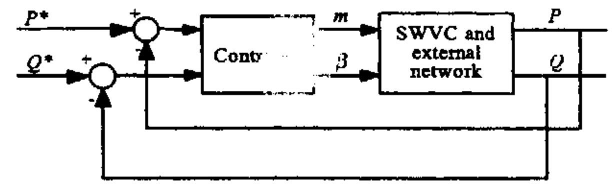

Fig. 6:Principle scheme of the P-Q SWVC control.

E_I of the e.m.f. generated on the AC side by a sine-triangle PWM converter is algebraically related to the DC voltage (fig. 7): $E_1 = m/(2\sqrt{2})V_{DC}$.

Between the output of the converter and the SWVC terminals (i.e. between points *A* and *B* of fig. 1), there is a double bipole the can be described by its pi-equivalent as in fig. 8 a). The network constituted by E_1 and this pi equivalent, seen from the SWVC terminals, in turn can be described as a Thevenin equivalent, as shown in fig. 8 b).

Neglecting the real part of Z_{th}, the following equations can then be written, relating (m,β) and (P,Q):

$$P = VI\cos\varphi = \frac{VE_{Th}(m)}{X_{Th}}\sin\beta$$
$$Q = VI\sin\varphi = \frac{VE_{Th}(m)}{X_{Th}}\cos\beta - \frac{V^2}{X_{Th}}\,. \tag{1}$$

where V, I and φ are the positive-sequence components of voltage and current at the terminals of the SWVC (point *B* of fig. 1) and the corresponding power angle, respectively. Rather obvious, E_{Th} is proportional to the DC voltage and the amplitude modulation ratio: $E_{Th}(m)=K_{Th}mV_{DC}$.

The (1) can be linearised, obtaining:

$$\begin{pmatrix}\Delta P\\ \Delta Q\end{pmatrix} = \mathbf{J}\begin{pmatrix}\Delta m\\ \Delta\beta\end{pmatrix} \qquad \mathbf{J} = \begin{pmatrix}\dfrac{\partial P}{\partial m} & \dfrac{\partial P}{\partial\beta}\\ \dfrac{\partial Q}{\partial m} & \dfrac{\partial Q}{\partial\beta}\end{pmatrix} \tag{2}$$

If C(s) is the controller matrix, the transfer matrix of the linearised, feedback-controlled system (indicating with lowercase letters differences of actual values and reference linearisation points) is:

$$\begin{pmatrix}p(s)\\ q(s)\end{pmatrix} = [\mathbf{I} + \mathbf{J}\mathbf{C}(s)]^{-1}\mathbf{J}\mathbf{C}(s)\cdot\begin{pmatrix}p^*(s)\\ q^*(s)\end{pmatrix}$$

where p, q, p^*, q^* indicate differences between P, Q, P^*, Q^* and the set-points used for the linearisation, and s is the Laplace transform variable.

To make the two channels of active and reactive powers independent it is sufficient to pose:

$$\mathbf{C}(s) = \mathbf{J}^{-1} g(s)$$

where, $g(s)$ is a scalar controller transfer function, and therefore obtain:

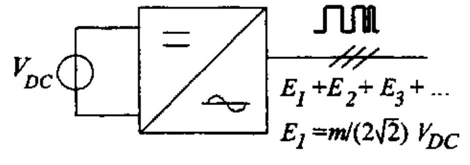

Fig. 7 Relationship between DC and first-harmonic AC voltage.

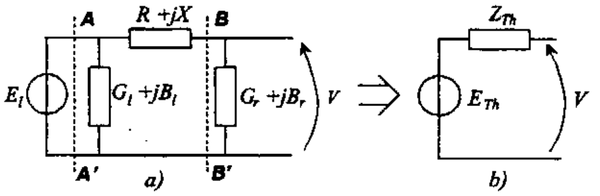

Fig.8: Thevenin industrial frequency equivalent of the set converter-filter-transformer.

$$\begin{pmatrix}p(s)\\ q(s)\end{pmatrix} = \mathbf{I}\,\frac{g(s)}{1+g(s)}\cdot\begin{pmatrix}p^*(s)\\ q^*(s)\end{pmatrix}$$

Because of the marked non-linearity of equations (1), and considered that β can be even some tens of degrees if X_{Th} is large, the linearisation of them around a fixed point is not satisfactory; then an adaptive control is to be implemented, that linearises the equations at each sampling time. This can advantageously be made by means of a discrete-time controller, e.g., using the forward-Euler transform $(s=(z-1)/\Delta T)$, and then anti-Z-transforming. Sampling times in the order of 10 ms are satisfactory: fig. 9 *a)* shows a transient constituted by the response of an SWVC having the nominal parameter shown in Appendix to a change in the (P^*, Q^*) signals, from (0,0) to (400kW, 200kVAr).

The electromotive force generated by the SWVC is constituted obviously by a fundamental component and some harmonics (fig. 7). Rather obvious, the currents the device delivers to an ideal sinusoidal network are much "dirtier" in case of small power exchanges than in case of large ones. This because in the first case the fundamental component of the voltage generated by the SWVC nearly equals the network voltage and the currents are therefore determined nearly only by the harmonics. This fact is illustrated in fig. 9 *b)* and *c)*, showing the current delivered by one of the three phases of the SWVC.

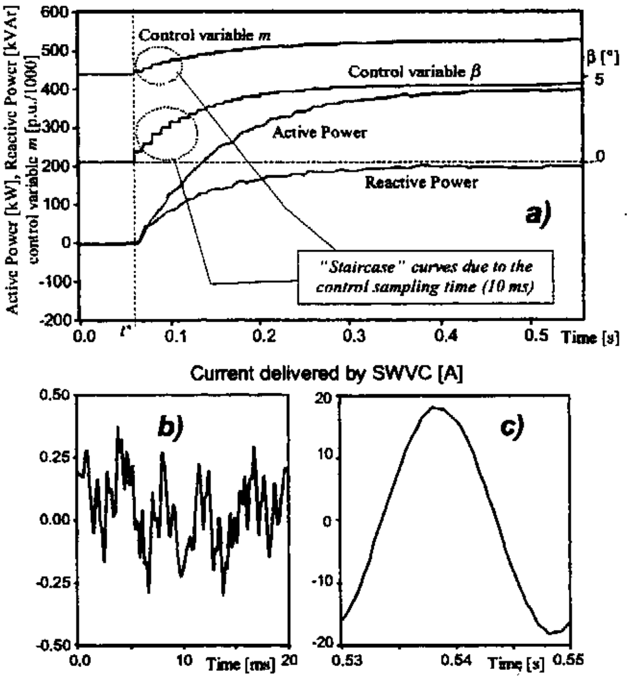

Fig. 9: Compensator response to a sudden request of P=400kW, Q*=200 kVAr for t=t*.*

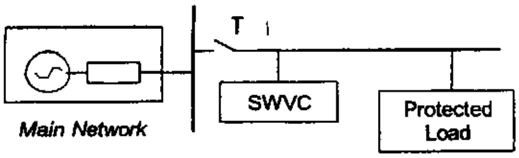

Fig. 10: A sample network showing parallel and islanded operations.

VI. ISLANDED OPERATION

In addition to operate connected in parallel with an active network, the SWVC can also feed a passive network, supplying to it both active and reactive powers.

Obviously, in this kind of operation the control logic is very different. In particular, the SWVC has to establish the network frequency. The two control variables m and β can then be used this way:

- β is kept constant, so that a sinusoidal system constituted by three sinusoidal waves with constant frequency and phase is generated;
- m is varied according to a control target. A natural choice is to set as a control target the regulation of the voltage at a particular network point, e.g., the SWVC terminals.

The switching from the P-Q operation (SWVC in parallel with an active network) to the islanded operation, and vice-versa, can be performed very smoothly with the SWVC. This is very important, since the device can somehow act as an Uninterruptible Power Source (UPS), as is easily seen from fig. 10, in which after the opening of the breaker **T**, the protected load can be fed by the SWVC operating in islanded mode.

Fig. 11 a) shows the active and reactive SWVC output corresponding to an abrupt opening of breaker **T** (at the time t=0.1s), while the compensator was in *stand-by*, i.e., when it was exchanging virtually no active and reactive powers with the network.

Fig. 11 b) shows the Protected Load voltage for the same transient.

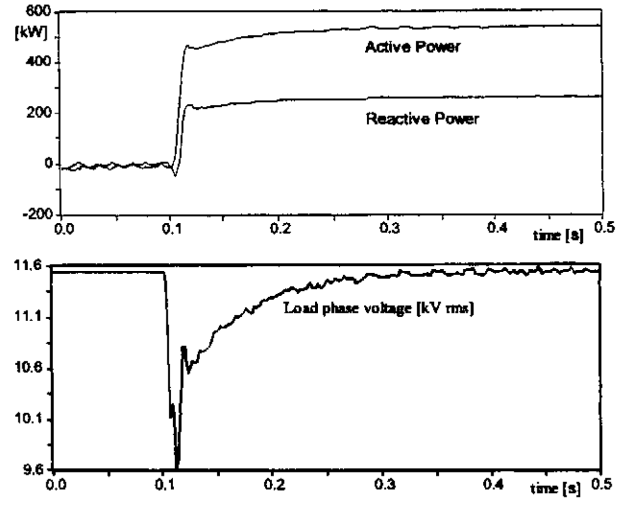

Fig.11: Transient following the abrupt opening of breaker **T** *of fig. 10 at t=0.1s, starting from SWVC in stand-by.*

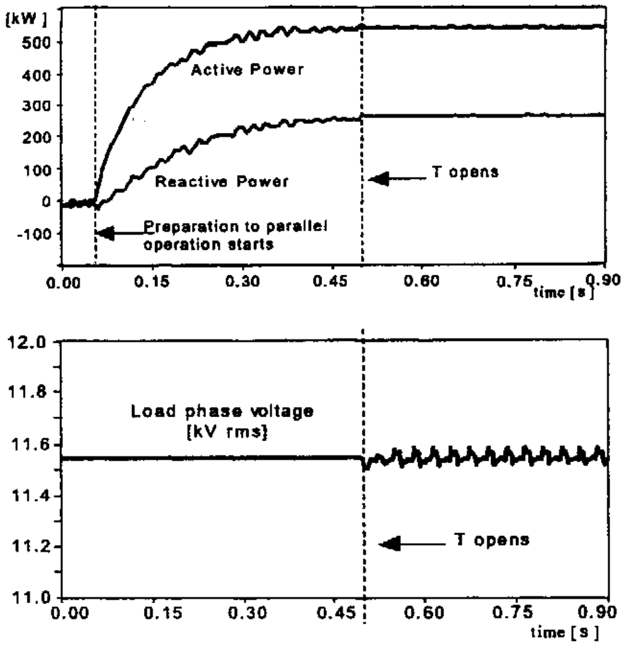

Fig. 12: Transient following the abrupt opening of breaker **T** *of fig. 10 at t=0.1s with predictive SWVC operation.*

In case there is some means to inform the SWVC in advance that the breaker **T** is to be opened (e.g. when a fault is detected and the protection logic is so that the **T** opening is retarded), the operation can be much smoother, since the SWVC, after receiving the signal that **T** will be soon open can switch to a control that has as target the minimisation of the active and reactive powers flowing within **T**, as shown in fig. 12.

VII. SOME DETAILS OF THE IMPLEMENTATION TECHNIQUES USED

A. Measuring rms values.

To measure rms values in ATP several techniques can be utilised. After some study it has been found that the use of the definition of rms realises the best compromise between speed and robustness:

$$A_{rms} = \sqrt{\frac{1}{T}\int_{t-T}^{t} a^2 dt}$$

This formula is suitable for continuous computation, if it is intended in terms of mobile mean. In general, The time T can be chosen as equal to the period T_s of signal a. However, if it is known as in most cases, that it is:

$$a(t) = -a(t - T_s/2)$$

it can be posed:

$$T = T_s/2$$

This choice allows A_{rms} to be more rapid in following the changes of the rms of a.

The core of MODELS code that implements this logic is (T is here called *RmsPeriod*):

```
...
DELAY CELLS(X2integral): RmsPeriod/timestep
  EXEC
    X2:=X*X
```

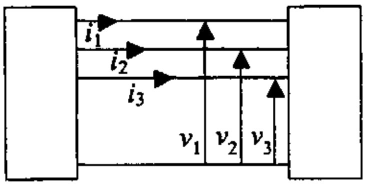

Fig. 13: Three-phase interface between circuits.

```
   LAPLACE(X2integral/X2):=1|/1|s
   temp:=(X2integral-
       delay(X2integral,RmsPeriod,1))/RmsPeriod
   Xrms:=sqrt(temp)
...
```

B. Measuring Active and Reactive powers

The measure of the three-phase active power flowing in a three-phase connection (fig. 13) is trivial, both in terms of instantaneous and averaged powers:

$$p_3 = \sum_{k=1,3} v_k \cdot i_k \qquad P_3 = \frac{1}{T}\int_{t-T}^{t} p_3(t)dt$$

where

p, v, i are is the instantaneous powers, voltages, currents
P are average powers.

As far as the *instantaneous* reactive power is concerned, there is not a uniform definition in literature.

For the purpose of simulation, particularly useful definitions of instantaneous reactive power and reactive power are:

$$q_3 = \sum_{k=1,3} v^*{}_k \cdot i_k \qquad Q_3 = \frac{1}{T}\int_{t-T}^{t} q_3(t)dt$$

where:

$$v^*{}_k(t) = v_k(t - T/4)$$

This definition that has in common with the three-phase instantaneous active power the characteristic of being constant if voltages and currents are such that the only non-zero symmetrical components are direct sequence ones. In addition, differently with other definitions, the active power Q_3 can be calculated as the *average*, and not the *maximum* of a quantity, that is a definite advantage for simulation purposes.

A MODELS code that implements these power definitions, and also makes some mobile-average filtering of the resulting signals is as follows (*period* is the known period of voltages and currents). Note, to avoid nearly useless computations, a minimum is posed on the model's timestep.

```
TIMESTEP MIN: period/400
DELAY CELLS(v1 v2 v3):100
DELAY CELLS(Pintegral Qintegral):400
HISTORY
  Pintegral {dflt:0} Qintegral{dflt:0}
  INTEGRAL(Pinst){dflt:0}
  INTEGRAL (Qinst){dflt:0}
  v1 {dflt:0} v2 {dflt:0} v3 {dflt:0}
INIT  delay4:=period/4  ENDINIT
EXEC
  Pinst:=v1*i1+v2*i2+v3*i3
  Qinst:=delay(v1,delay4)*i1+delay(v2,delay4)*i2+
                              delay(v3,delay4,1)*i3
  Pintegral:=INTEGRAL(Pinst)
  Qintegral:=INTEGRAL(Qinst)
  P:=(Pintegral-delay(Pintegral,TmeanP))/TMeanP
  Q:=(Qintegral-delay(Qintegral,TmeanQ))/TMeanQ
ENDEXEC
```

VIII.CONCLUSIONS

- The ATP/MODELS is a program very suitable to simulate power electronic devices having very complex controlling logic; however, the fixed-step choice of ATP is rather limiting for the simulation of PWM inverters;
- the great power and flexibility of MODELS is adequate to simulate complex control of SWVC's, in particular, the TIMESTEP directive is suitable for simulating the behaviour of discrete-time control systems;
- the sample simulations proposed show how Static Watt-VAR Compensators (SWVC) are devices very useful in power systems, due to their great flexibility and speed of control.

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APPENDIX: NOMINAL PARAMETERS OF THE SWVC CONSIDERED

The considered SWVC has the following nominal quantities:

Power: 1 MVA
Voltage: 20 kV
Frequency: 50 Hz
Carrier frequency: 1050 Hz