CONTROL AND PLANNING OF 50/60 Hz INDUSTRIAL SYSTEM LOAD FLOWS

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ABSTRAC

In this paper a 50/60 Hz load flow (LF) model for electric power system (EPS) linked by static frecuency converters (SFC) is proposed.

In this model the diferent operation modes of CEF are considered: a) by power-frecuency control and b) by fixed active power control.

The model goodness based on a Newton algorithm, is showed through a realistic case.

INTRODUCTION

For historical reasons, in the large-scale mining industry in Chile (for example, Codelco-Chile, SQM), there exist EPS whose consumption operates at 50 Hz or 60 Hz, producing two interconnected networks.

The energy which these require is provided in part by their own generators, which makes it necessary to transfer the energy by means of rotatory and/or static frequency converters, which link together both networks, in order to make up the power deficit in the EPS.

Other types of 50/60 Hz EPS which must transfer energy at loads at 60 Hz are found in shipyards where ships dock whose electric machinery must necessarily be fed at that frequency. However, although these systems present a series of particularities which are outside the area of this paper, a great deal of the industrial-mining perspective employed in this work could be applied directly to that area.

Due to the technological advances in the field of power electronics, today frequency conversion is usually carried out by means of SFC, transferring power as a function and in the direction of the most important area of consumption [1] The arrival of this equipment has made it necessary to incorporate them into the planning and control procedures and models which deliver, in particular, the state of the system when this has reached an equilibrium, i.e. power flows. Also, the use of SFC brings with it the following advantages over the rotatory equipment: (a) the SFC are more efficient, which results in an energy economy, (b) a lesser possibility of interference with the production because it is simpler to operate and (c) a very rapid response time to variations in charge and generation.

The state of the art of a problem similar to that which is of concern to us is known in the literature as LF ac/dc. This is applicable to transmission and distribution systems and it shows us that one of the ways to include this equipment is through either sequential procedures of LF-dc/LF-ac [2,3] or through the newtonian search for a group of equations which incorporate the expressions which control the behaviour of the inverser-rectifier set in the jacobean matrix [4,5,6,7]. However, due to the fact that the actives transmitted and the reactives consumed in a dc link, in a SFC, vary according to different control protocols, none of these tools can be applied to the particular problem that is of concern to us.

In this work a procedure for the calculation of LF based of the Newton-Raphson algorithm which is capable of considering the operation of the SFC in constant power or slack power (frequency control) is presented. The former is achieved, basically, by finding a relation between the actives transmitted and the reactives consumed by the SFC and incorporating it into an ac formulation of the LF.

The strength of the model was tested through the standard IEEE systems incorporating SFC and a realistic case based on large-scale chilean mining. Although in all the cases the results were consistent, given the importance that this last system has, only this one is described in detail in this publication.

1.- INCORPORATION OF THE SFC IN THE AC NETWORK

In the following sections, we will assume, for reasons of explanation that the 60 Hz system is the one that is deficient in power.

Also, in general we must keep in mind that no matter what is the method of operation of the SFC, the reactive requirements and their

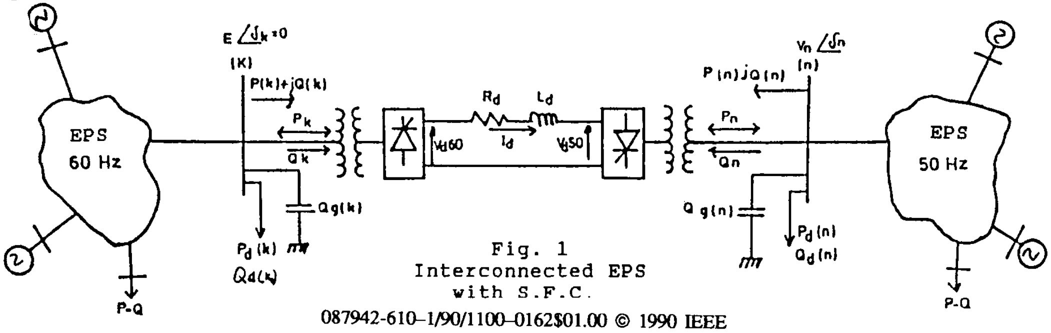

Fig. 1
Interconnected EPS
with S.F.C.

harmonic filtering necessities are provided through a capacitor bank located at its terminals (see fig. 1). Eventually there could also exist a certain level of consumption both of actives as of reactives attributable to any load connected there. With the objective of establishing a model for the SFC, we will consider next its possible methods of operation.

1.1.- A MODEL OF THE SFC IN OPERATION MODE WITH FREQUENCY CONTROL

In this operation mode, the SFC regulates (adjusts) automatically the active power to be transferred [8], that is, its magnitude and direction as a function of the frequency deviations of the 60 Hz system. (see fig. 1)

The SFC, with frequency control behaves basically like a slack node, as far as the active balance is concerned. However, the reactives which this consumes for its operation are closely linked with the active power which is transferred, through a constant power factor [14].

Additionally, in this operation mode, the SFC does not control the voltage at its ac terminals, rather it adapts them to the active and reactive levels engaged and to the voltage profiles of the system. From this point of view, this characteristic of the SFC makes it comparable to a load node.

With these antecedents the definition of bus bars established by LF theory is insufficient. Therefore, in this publication a definition of the node is proposed in the following terms:

We will call a "free node" that node on the 60 Hz side associated with the SFC which is considered to be the angular reference and whose power will be adjusted so as to guarantee the active balance in the 60 Hz system thus assuring the power factor specified in the SFC.

The above definition is conditioned in part by the fact that the slack node of the 50/60 Hz EPS must be located on the 50 Hz side and that the node on the 50 Hz side associated with the SFC is always the charging node.

With these antecedents and referring to fig. 1 the equations which control the power balance at the node (k) are given as:

$$Qk = cte*Pk \qquad (1)$$
$$cte = \tan(\phi) \qquad (2)$$
$$Q(k) = Qg(k)-Qk-Qd(k) \qquad (3)$$
$$P(k) = (\pm)Pk-Pd(k) \qquad (4)$$

Considering that the active power in the SFC flows from the 50 Hz side to the 60 HZ side the conditions expressed in equations (1) TO (4) give us:

$$Q(k)+cte*P(k) = S \qquad (5)$$
$$S = Qg(k)-Qd(k)-cte*Pd(k) \qquad (6)$$

Equation (6) reflects the SFC operating conditions with frequency control.

In any distribution network the variables Pd(i) and Qd(i), as well as Pk and Qk (fig. 1) are outside our control, given that they are determined by the consumer.

The control variable S of equation (6) is in concordance with the state variable, node voltage (k), at the 60 Hz terminal of the SFC.

1.2.- MODEL OF THE SFC IN CONSTANT POWER OPERATION MODE

In this operation mode, the operator of the SFC establishes the direction of the energy transference and the quantity of power to be transferred [1,8].

As in the operation mode for frequency control, this operation method is not capable of controlling the voltage at the terminals. In accordance with this and keeping in mind that Qk = Cte*Pk, the bus bar associated with the node (k) (fig. 1) of the SFC, behaves exactly like a load node.

We can therefore deduce from this that the node associated with the 50 Hz terminal of the SFC must also be a P-Q type.

1.3.- MODEL OF THE SFC IN THE OPERATION MODE WITH VAR COMPENSATION

A special case, for operations of practical interest, is that which results upon considering the VAR which the compensation bank gives is close to those which the SFC requires for its operation.

In these circumstances, the equations which control the power balance in the node (k) are given by:

$$Qg(k) = Q(k) = cte*Pk$$
$$Q(k) = Qg(k)-Qk-Qd(k) = -Qd(k) \qquad (7)$$

Taking into account that the node (k) can be taken as a reference, (7) is the equation which allows us to obtain |E|.

2.- 50/60 Hz LF MODELS

The LF 50/60 Hz model proposed in this publication considers the well known models for active and passive components for an ac power network for conventional LF studies [13] (the SFC is evidently an exception to the above).

In accordance with the models proposed for the SFC three 50/60 Hz LF models can be established. All these models are based on the solution for a power flow in a 60 Hz network which we will call LF-60 Hz and with a load flow in the network of 50 Hz which we will call LF-50 Hz.

2.1.- LF MODEL WHEN THE SFC OPERATES WITH FREQUENCY CONTROL

When the SFC operates in this way, the 60 Hz node (k) behaves like a "free node".

If we consider the 60 Hz network, we can state the following group consisting of equations to be resolved by means of Newton's method using polar formulation:

$$(DP \quad DQ \quad DS)^t = (J) * (D\delta \; DV \; DE)^t \qquad (8)$$

whit:

$$J = \begin{bmatrix} P_\delta & Pv & Pe \\ Q_\delta & Qv & Qe \\ S_\delta & Sv & Se \end{bmatrix}$$

The submatrixes P_δ, Pv, Q_δ, and Qv indicate the variation of P and Q in respect of δ and V [9]. The submatrixes Pe, Qe, S_δ, Sv, and Se come from the modeling of the node (k) and measure the sensibility of P, Q and S in respect of δ and E. The expressions of these are given in detail in Annex 1.

Once the group of equations which define LF-60 Hz have been resolved, the level of active and reactive power in the node (n) has been determined, based on equations (3) and (1). In consequence, for the 50 Hz side the SFC must be treated like a load node when the group of equations for the LF-50 Hz are resolved:

$$[DP \quad DQ]^t = [J] * [D\delta \quad DV]^t \qquad (9)$$

2.2.- LF MODEL WHEN THE SFC OPERATES AT CONSTANT POWER

When the SFC operates in this way, as was seen in 1.2. the node (K) behaves like the load node. Therefore, from the 50 Hz side, the SFC at 60 Hz is reflected like a load bar at node (n).

One can, therefore, establish a group of equations to be resolved simultaneously and separately for both EPS. This is:

$$[DP \quad DQ]^t = [J(50)] * [D\delta \quad DV]^t \qquad (10)$$

$$[DP \quad DQ]^t = [J(60)] * [D\delta \quad DV]^t \qquad (11)$$

2.3.- LF MODEL WHEN THE SFC OPERATES WITH REACTIVE COMPENSATION

With this method of operation upon assuming an injection near to or equal to the consumption of VAR of the equipment, in accordance with equation (7) it is only necessary to know Qd(K) in order to be able to state the system of equations which determine LF-60 Hz.

Notice should be taken that for analogue reasons to those mentioned in section 1.1 the node (k) of the SFC does not behave exactly, in this case, like a slack node, but instead it turns out to be a special type of "free node", which we could call "node Q-δ" (given that it is considered to be an angular reference).

In this case, as in section 2.1 two LF must be resolved in a sequential way. For the LF-60 Hz the system of equations is given by:

$$[DP \quad DQ \quad DQ(k)] = [J]*[D\delta \quad DV \quad DE] \qquad (12)$$

The calculation of LF-60 Hz allows us to obtain Pk = Pn. This last value replaced in equation (1) determines the value of Qn. In this way we are in a position to resolve the LF-50 Hz considering the bus bar (n) as a load node.

3.- APPLICATIONS

The advantages of the proposed model were evaluated in a realistic EPS in which the topology basically corresponded to that of Codelco-Chile, El Teniente Division; not so the consumption, which was estimated on the basis of the installed power.

As you will remember, in all the models described, the LF-50 Hz considered the node (n) as a load bus bar. Therefore, the simulation of this, from the comparative point of view (storage, iteration, CPU time, etc.) is irrelevant. Due to the preceding and because of problems of space, we will now concentrate on the details concerning the LF-60 Hz.

The EPS-60 Hz contains 17 nodes (fig. 2) of which 14 correspond to load nodes and 2 correspond to power and voltage control nodes, one of which eventually becomes a slack node in accordance with the method of operation of the SFC. Node (5) is the node which is connected to the SFC looked at from the 60 Hz side (node k).

A standardized selection of parameters gave us the structure of a data base for the lines, cables and transformers, the detail of which is given in tables 1 and 2 [12].

Experience with LF systems of distribution shows us that a badly conditioned system, from the power point of view, presents divergences even in the formulation of a first order gradient (polar Newton or cartesian). From this perspective, so as to test the strength of the proposed model, factors of demand and unitary diversity for all the network were considered. As a consequence of this, depending on the type of bus bar, one has the power set shown in table 3.

With reference to the one line diagram shown in fig. 2, there are tables 1, 2, and 3. Table 3 does not contain the information which describes nodes (1) and (5). This is due to the fact that these change their condition depending on how the SFC functions. This is why the type of bus bar that they will become is described in the specific application.

3.1.- APPLICATION 1: FREQUENCY CONTROL

In this case it was considered that the SFC would operate in the frequency control or slack power mode. A factor of 0.9 was assumed for the power factor of the SFC and the description of nodes (1) and (5) is that given in table 4.

Assuming that in this case there exists at the SFC terminals a capacitor bank whose specifications assume a maximum level of power transference (10MW) in the equipment: necessarily there will be surplus VAR when the equipment delivers a lower level of power (which will be delivered to the network) and due to the inductive nature of this, reductions in the voltage drop in the area of the connection will be obtained.

3.2.- APPLICATION 2: CONSTANT POWER

In this operation mode the SFC functions with a power level fixed by whomever operates the equipment.

Bus bar (5) is characterized as the load node in which the actives and reactives of the SFC are those corresponding to Application 1. The selection of these power levels in the SFC is made for reasons of comparison. Node (1) is considered as being the slack bus bar. Table 5 shows the different parameters of these nodes.

3.3.- APPLICATION 3: VAR COMPENSATION

Finally the case is proposed in which the bank which feeds the SFC on the 60 Hz side provides exactly the reactives that this consumes. In this case bus bar (5) is characterized as a bus bar Q-δ, in which the actives are free. Node (1) should be considered as a PV node. The parameters of these nodes are given in table 6.

The results of the LF models with

frequency control, with power control and reactive compensation are given in detail in tables 7, 8, and 9 respectively. There is shown: the voltages, the losses, VAR consumed and power transmitted by the SFC, the CPU times and the number of iterations, for each case.

4.- ANALYSIS OF THE RESULTS

The reading and interpretation of the results show that they are consistent. In all the cases the proposed LF model converged. The error criteria considered was 0.0001.

The voltage profiles, despite the fact that they were below the levels normally accepted, corresponded to what was expected, given the considerations relative to consumption and the unitary value adopted for the factors of demand and diversity that were adopted.

The differences in the results between the models with frequency control and power control, given that the reference node was changed, is expressed in the voltage phases. Also, given that for the second case a power specification was chosen that was identical with that of the first case, both the voltages and the losses are identical.

The results of the model with VAR compensation should be compared with those of the model with frequency control. Therefore, given that the reference node in both cases is the same, we can say that the most important difference; in voltage it is produced at node (5) and is -2.3%, in the phase it is produced at node (4) and is -7.5%, in the losses it becomes a 4% error, and in the transference of actives it is +5.8% and the discrepancy in the VAR consumption is +5.8%. Take note that although the most important error is seen in the phase, this is not relevant as it corresponds to an angular quantity that is very small.

We can, finally, say that the cpu times in seconds (which are very good) are relatively similar. The SFC model with VAR compensation is 5.5% faster than the exact model with frequency control. Even so, for this application this is only a difference of 110 (ms). As regards difficulties in implementation, a subjective judgement would give the highest marks to the model with frequency control, followed by the model with VAR compensation and finally by the model with power control.

CONCLUSIONS

The LF analysis in the EPS is an important problem which, due to the equations which control the behaviour of the static equipment, proved more complex to solve.

A LF 50/60 Hz model is proposed in this publication which considers the means of control of the SFC. This not only permits that the voltage profile on both the 50 Hz side as well as the 60 Hz side of a 50/60 Hz EPS can be determined, but also it is capable of predicting the power interchange (magnitude and direction) when the SFC operates in the slack mode. Perhaps one of the most relevant aspects of this modelling is the fact that a dynamic problem (frequency control) is tackled from the static point of view, by means of the concept of the free node and the $Q-\delta$ node. This last is a natural extension of the concept of the PV node.

Even though the incorporation of SFC in the constant power method of operation is extremely easy, (using the LF procedure) lamentably in practice it is not frequently used.

Although the $Q-\delta$ means of operation of the SFC does not exist in reality, it is a working hypothesis which is validated in large part by operations in real conditions. From the computing point of view, it is an individual case of great interest.

The model proposed is general and efficient. Its use permits the incorporation of SFC to LF of the 50/60 Hz EPS. In its results precisely those points and situations which present problems could be seen thus making possible the planning of alternative solutions for the design and expansion of networks of this type.

Given that these types of equipment have been developed principally for the transmission of energy between points that are far apart, by means of DCHV and for mono-frequency EPS, its application as a frequency converter system is rare in the world and its models in this context have not been suitably dealt with.

It is important to also emphasize the versatility of the software developed, due to the different alternatives for its use and the facilities for its employment, which makes it very attractive for applications in both the industrial and teaching areas.

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LIST OF SYMBOLS

Q(k): reactive power at node (k).
P(k): active power at node (k).
Qg(k): power injected at node (k).
Qk: reactive power consumed by the SFC on the 60 Hz side.
Pk: active power transferred by the SFC.
Qd(k): reactive power demanded by node (k).
Pd(k): active power demanded by node (k).
ϕ : SFC power factor angle.
DP(i): variation of the active power at node (i).
DQ(i) tion of the reactive power at node (i).
Dδ(i): variation of the voltage angle at node (i).
DV(i): variation of the voltage module at node (i).
DS : variation of S (eq. 6) at node (k) (fig. 1).
DE: variation of the voltage module at node (k).
DQ(k): variation of the reactives at node (k).
Pd: continuous power.
Id: dc link current.
Vd: dc link voltage.
V: voltage at node (i).
δ: voltage angle at node (i).
E: voltage at node (k).
D: indicates variation.

ANNEX 1

JACOBEAN EQUATIONS IN THE FREQUENCY CONTROL MODE FOR SFC.

The active and reactive powers at each node, as well as the expression which relates the powers Pk and Qk at the free node are given by:

$$P(i)=\sum_{j=1}^{n} V(i)*V(j)*Y(i,j)*\cos[\delta(i)-\delta(j)-\theta(i,j)] \qquad (13)$$

$$Q(i)=\sum_{j=1}^{n} V(i)*V(j)*Y(i,j)*\sin[\delta(i)-\delta(j)-\theta(i,j)] \qquad (14)$$

$$S = Q(i) + cte * P(i) \qquad (15)$$

Where, (13) is applied to the active powers at the load and controlled voltage nodes, (14) to the reactive power at the load nodes and (15) to the free node (bus bar k).

The group of equations to be solved, aligned around an operation point, is given in the following matrix-expression:

$$\begin{bmatrix} DP \\ DQ \\ DS \end{bmatrix} = \begin{bmatrix} P_\delta & Pv & Pe \\ Q_\delta & Qv & Qe \\ S_\delta & Sv & Se \end{bmatrix} \begin{bmatrix} D\delta \\ DV \\ DE \end{bmatrix} \qquad (16)$$

where: Pe = dP/dE, Qe = dQ/dE, S_δ = dS/dδ, Sv = dS/dV, Se = dS/dE, P_δ, Pv, Q_δ, and Qv correspond to the sensitivities of P and Q in respect of δ and V respectively. The symbol "d" refers to the partial derivation.

TABLE 1
Parameters of lines and cables. f=60Hz. MVA base=85

node	R	X
1-2	0.03	0.1267
1-3	0.0497	0.1920
1-4	0.0497	0.1920
3-6	0.0427	0.1651
4-6	0.0427	0.1651
9-10	0.0051	0.0396
9-12	0.0051	0.3967
12-13	0.0028	0.2160
15-16	0.0018	0.0144
16-17	0.0018	0.2160
10-12	0.0028	0.0216

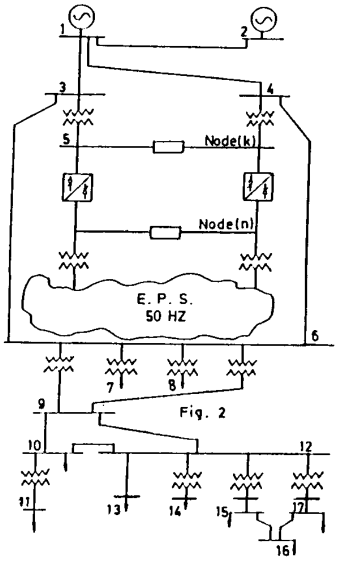

Fig. 2

TABLE 3
Description of nodes
MVA base=85. f=60 Hz

node	Pg-Pc	Qg-Qc	type	V
2	0.28000	-	PV	1.05
3	0.00000	0.00000	PQ	-
4	0.00000	0.00000	PQ	-
6	0.00000	0.00000	PQ	-
7	-0.3000	-0.2100	PQ	-
8	-0.3000	-0.1850	PQ	-
9	0.00000	0.00000	PQ	-
10	-0.0309	-0.0191	PQ	-
11	-0.0400	-0.0240	PQ	-
12	0.00000	0.00000	PQ	-
13	-0.0069	-0.0020	PQ	-
14	-0.0589	-0.0360	PQ	-
15	-0.0250	-0.0118	PQ	-
16	-0.0125	-0.0071	PQ	-
17	-0.0765	-0.0288	PQ	-

TABLE 7
Frequency Control
(free node)

node	V(0/1)	degrees
1	1.0500	5.4712
2	1.0500	7.4109
3	0.9414	1.3069
4	0.9414	1.3069
5	0.9284	0.0000
6	0.8571	-2.7655
7	0.8057	-6.8249
8	0.8035	-7.4843
9	0.8267	-5.8507
10	0.8229	-6.2022
11	0.8213	-6.3417
12	0.8222	-6.2755
13	0.8221	-6.2876
14	0.8206	-6.4258
15	0.8213	-6.3752
16	0.8210	-6.4016
17	0.8209	-6.4199
cpu time		1.97 s.
iterations		5
losses		0.08470
Pk		0.05758
Qk		0.02764

TABLE 8
Power Control

node	V(0/1)	degrees
1	1.0500	0.0000
2	1.0500	1.9396
3	0.9414	-4.1643
4	0.9414	-4.1643
5	0.9284	-5.4709
6	0.8571	-8.2367
7	0.8057	-12.296
8	0.8035	-12.955
9	0.8267	-11.332
10	0.8229	-11.673
11	0.8213	-11.813
12	0.8222	-11.747
13	0.8221	-11.759
14	0.8206	-11.897
15	0.8213	-11.846
16	0.8210	-11.873
17	0.8209	-11.891
cpu time		1.95 s.
iterations		5
losses		0.08470

TABLE 9
Frequency Control
(Q-δ node)

node	V(0/1)	degrees
1	1.0500	5.3117
2	1.0500	7.2513
3	0.9360	1.2081
4	0.9360	1.2081
5	0.9071	0.0000
6	0.8508	-2.9163
7	0.7990	-7.0399
8	0.7967	-7.7101
9	0.8202	-6.0489
10	0.8164	-6.4061
11	0.8148	-6.5478
12	0.8157	-6.4805
13	0.8156	-6.4928
14	0.8140	-6.6332
15	0.8147	-6.5818
16	0.8145	-6.6086
17	0.8143	-6.6273
cpu time		1.88 s.
iterations		5
losses		0.08810
Pk		0.06094
Qk		0.02925

TABLE 2
Parameters of Transformer. MVA base=85
(f= 60 Hz)

node	R	X
3-5	0.0427	0.6605
4-5	0.0427	0.6605
6-7	0.0123	0.1714
6-8	0.0139	0.1974
6-9	0.0073	0.1561
10-11	0.0059	0.0447
12-14	0.0034	0.0321
12-15	0.0033	0.0261
12-17	0.0024	0.0271

TABLE 5
Description of nodes (1) and (5). Constant Power
MVA base=85

node	Pg-Pc	Qg-Qc	type	V
1	0.07176	-	slack	1.05
5	-0.0624	-0.0320	PQ	-

TABLE 4
Description of nodes 1 and 5 with frequency control. MVA base =85

node	Pg	Qg	type	V	Pd	Qd	Qg(k)	S	Cte
1	0.07176	-	PV	1.05	-	-	-	-	-
5	-	-	free	-	0.12	0.075	0.0706	-0.062	0.48

TABLE 6
Description of nodes 1 and 5 with VAR compensation. MVA base 85

node	Pg-Pc	Qg-Qc	type	V	Cte
1	0.07176	-	PQ	1.05	-
5	0.00000	-0.0750	Q-δ	-	0.04800