THE PRELIMINARY TEST OF THE STATIC POWER SUPPLY FOR JAPANESE PROTON SYNCHROTRON

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Abstract

It is a recent trend to design the power system for a proton synchrotron by a direct connection of the power supplies to the power lines,[1] for giving a solution to the mechanical failure in the motor generator set, which have been usually installed between the power supply and the power line to avoid the direct disturbance of varying load to the power line.

In Japanese proton synchrotron (8 GeV - 12 GeV)[2] the peak reactive power is 14 to 19 MVar depending on a designing point of the cyclo-converter set. Without any protecting device, roughly 3 % voltage fluctuation will be induced on the city power line.

The report introduces one method, a function of which is the continuous and quick response compensation of the voltage fluctuation by thyristors and with associated reactors. The model of the proper scale was installed to test the method in the power system of the model magnet. The reactive power has been completely compensated and the voltage fluctuation has been decreased from 3 % down to 0.5 %. The technical difficulties which will be supposed in an actual machine have been overcome and the cost estimation has shown much more economical merit than such methods that use the saturable reactors, multi-banks of capacitors with thyristor switches, and the motor generator set.

Introduction

A pulsed load such as the magnet of the proton synchrotron causes voltage fluctuations in the power line, when the power supply is directly connected to it. On the other hand, four requirements must be met in the above-mentioned case.

(i) The induced voltage fluctuation by pulsed load must be within the permissible value at the connecting point to high voltage transmission power line.

(ii) The energy swing must be satisfactorily distributed throughout the transmission system.

(iii) The power line must be kept clean from the harmonic current.

(iv) More reliability and flexibility than obtained from existing MG set.

The main function of the static power supply is suppression of the induced voltage fluctuation which is caused by the relation between the fluctuated reactive power of cyclo-converter set and the reactive impedance of the transmission line. The situation is similar to the cases in heavy industries, for example, arc furnaces and rolling mills controlled by motors. The former is the flicker of an arc discharging current and the latter is that of a repetitive cycle of acceleration and deceleration of the motor in the steel mills. But the environmental condition is quite different. The laboratory is sited in the new city for the scientific research and the education. The flicker and the harmonic current will give harmful effects on other laboratories and institutes.

We are aiming to achieve a value of 1 % in voltage fluctuation and 0.5 % in harmonic voltage on the 66 kV line.

Flicker Suppressor

The magnet current and load quantities are shown in Fig. 1 as well as the system impedance. We can expect 3.2 % voltage fluctuations from the following equation,

$$j\ 1.663\ \%\times 14\ \text{MVar}/10\ \text{MVar} = 2.3\ \%$$

Many compensation methods have been reported. Among these the following systems have been considered.

A) Saturable reactor and shunt capacitors

Figure 2 shows the principle of this system. Complete and continuous compensation can be expected. The response is fast. But the system is rather expensive. For instance, the estimated cost is shown in Table 1 for 10 MVA. In our case the power to be compensated is 22 MVA. So the cost exceeds 250 million yen.

Table 1. Cost of flicker suppressor using saturable reactor, for 10 MVA.

Subjects	Cost in Yen
Oil Breaker 84 kV 600 A	5,800,000
Mutual Reactor	6,720,000
Saturable Reactor Transformer	81,890,000
Delta Connection Reactor	3,250,000
Capacitor for 2nd Harmonics	11,210,000
Reactor for 2nd Harmonics	6,000,000
Discharging Coil	660,000
Capacitor for 5th Harmonics	11,880,000
Reactor for 5th Harmonics	1,800,000
Discharging Coil	660,000
Monitor	1,010,000
Assembling	1,560,000
TOTAL	132,440,000

B) Step capacitors with thyristor switches

In Japan, the average cost by rough estimation of reactors and capacitors is 2,000 yen/kVA and 700 yen/kVA respectively. The cost of the capacitor being lower than the reactor by factor of 3 leads us to consider the compensation by capacitors.

The system of step capacitors is most common in a field of heavy industries for the suppression of flickers. The key point of this system is the magnitude of step. Infinite number of capacitor steps must be prepared for complete compensation. To achieve less than 1 % flickers, we need 3 steps, so 3 banks of capacitors. Table 2 shows a brief description of this system applied to the steel mills. The cost of this system is 150 million yen for our case. But it jumps up to 200 million yen if we want to reduce flicker down to 1 %.

Table 2. Compensation of reactive power by capacitor step for steel mills.

Power of Thyristor	4250 kW x 2
Max. Reactive Power	13,000 kVar
Max. ΔV without Compensation	± 3 %
Capacitor for Compensation	5000 kVA x 2
Max. ΔV with Compensation	± 1 %

C) Continuous compensation by thyristors with shunt capacitors

The thyristor associated with the reactor can change the reactive current by varying the firing angle of the thyristor. Therefore the variation of reactive power in the power supply for magnets, cyclo-converter set, can be compensated by the thyristor control.

The reactive power itself cannot be compensated but it can be done by shunt capacitors.

The system is elegant in principle but it has not yet been realized in Japan. The technique and the cost have never been evaluated, so we decided to test the system.

The model power supply which was prepared for testing the serial model magnets of the main ring was used for the present experiment.

Test of the Model Static Power Supply

Figure 3 shows the system of the test set and Table 3 gives a brief description of the model power supply. The system is a conventional MG set and SCR have been combined. The MG set has a large power margin, therefore we could not obtain the voltage fluctuation at the output terminals of the MG set. The reactor is inserted between the MG set and the SCR as shown in Fig. 3. This can simulate the impedance of the actual power line at the connecting point (Tsukuba, 50 km apart from Tokyo). Table 4 shows the specification of the flicker suppressor for the test.

Figure 4 shows the control unit of the flicker suppressor, we call it TQC which means the thyristor Q control. The V is shifted 90° in phase from V_S as shown in Fig. 4-A and it varies proportional to V_S. It is superposed to V_L from the current transformer detecting the load current of the power supply. The situation is shown in Fig. 4-A and B for minimum and maximum load current respectively.

Table 3. Existing power supply for model magnet.

Motor	3 φ 50 Hz 3.3 kV 125 kW
Generator	3 φ 50 Hz 3.3 kV 650 kVA (nominal)
SCR	100 V 1750 A x 3
Load Magnet	2500 A max 12 kG

Table 4. Test set

Simulating reactor	3 φ 50 Hz 0.54Ω/phase
SCR	3 φ 50 Hz 420V 580 A
Capacitor	3 φ 50 Hz 3.3 kV 300 kVA
Protector	3 φ 50 Hz 3.3 kV 400 kVA

At no load, V_L is equal to zero and $V-V_L$ cross the triggering level of the pulser at zero phase angle of the thyristor. The maximum current flow into the thyristor. The TQC is at full rating. When the load current of the multi-phase cyclo-converter decreased, $V-V_L$ cross the triggering level giving an appropriate delay of phase angle to the thyristor in TQC. The TQC current is decreased down to cancel the increased power of the cyclo-converter.

The total power, TQC power plus converter power, is always kept to be constant. Actually phase angle is limited between 35° and 90°, considering the fluctuation of the supply voltages and other factors. Less than 35° and over than 90° is prohibited. The gate circuit can protect the error operation.

The results are shown in Fig. 5 as A, B, A-C and B-C. A and B are with and without the flicker suppressor respectively. A-C and B-C are with shunt capacitors for both cases to compensate the reactive power. The power swing of 212 kVar was reduced to 36 kVar. The voltage fluctuation of 2.9 % was decreased down to 0.8 %. Due to the incomplete control of TQC, 36 kVar is still remained to be compensated. As shown in Fig. 4, the control of TQC is rather simple and not electronic. In actual machine, it is not decided yet whether more precise computer control or rather simple control is adopted. In any case, more complete compensation of reactive power can be expected with more precise control unit.

The impedance of the test system is calculated as 0.17 + j 0.90 % for 100 kVA base. This is slight different from the actual impedance of the system (0.19 + j 1.66 % for 10 MVA base), but the difference is not important. As only the basic problems, for example, compensation of the reactive power, quick response, simple control of the firing angle of SCR, and reliability of the instrument, are concerned the test system has shown the successful results.

Interesting results are given in A-C and B-C. As already described, the fluctuating part of the reactive power has been compensated to a great extent by varying the phase angle of SCR. On the other hand, the power factor can be expected to be improved by shunt capacitors in cases A-C and B-C.

In A-C, the voltage fluctuations increased with shunt capacitor and also in B-C. It seems the shunt capacitors stimulate the voltage fluctuations. This comes from the harmonic current generated by the cyclo-converter set. It used vast amount of thyristors, therefore, can generate the great harmonic current. Particularly when the converter flip to the inverter, as at just moment of the lag end of the flat top in the current pulse, the phase angle of the thyristor, goes to beyond 90° and so generate the great harmonic current. This flows into the power system and excites the resonance. This will be explained in the following sections.

The test gave us many technical know-hows and also the prospect in success. The actual flicker suppressor (TQC) is designed and is given in Table 5 with cost estimations.

Table 5. Specifications and cost of TQC.

Component	Specification	Cost in Yen
Transformer	6.6kV/1.21kV,50Hz, 14MVA,3	19,500,000
Reactor	1.2kV, 50Hz,14MVA 3	12,800,000
Thyristor in cubicles	2.5kV, 400A, 18 parallel, 2 arms 3	32,300,000
Control		1,500,000
Line trap	L 260 H, 6.6kV C 0.3 F, 6.6kV	3,700,000
Capacitors for filters	2 MVA for 3rd 3 MVA for 5th 3 MVA for 7th 6 MVA for higher	28,390,000
Breaker, switches and protection		11,500,000
Connection and adjustment		8,400,000
Total		118,090,000

The estimated cost was minimum among the considered alternative plans. The advantages of the method are summarized as follows.

i) continuous and complete compensation of reactive power
ii) simple control of thyristor
iii) quick response
iv) inexpensive
v) easy maintenance

Harmonic current

The problem of the harmonic current has never been discussed seriously in a field of accelerators, in spite of using great power of thyristor. On the other hand, it has been well known that the thyristor generates the harmonic current and deforms the fundamental wave of ac line.

The great power of rectifier using the thyristors is the recent techniques applied to many fields. One of the fields is the electrolytic process in aluminum refinement. In fact, a Japanese company pollute recently the 66 kV line with harmonic current from 12 phase 100 MVA thyristor rectifier. The resonances were stimulated by it at several points on the same grid near our laboratory. The power factor improving capacitors installed at the other consumers was forced to be overloaded.

The power company has begun to make a regulation on harmonic currents. The only one existing is the engineering recommendation by the Electricity Council in England at 1967.[3] It proposed the 0.5 % voltage distortion limit at the higher voltage network. The permissible limit has become gradually also the standard in Japan.

In this test, we can see the abnormal voltage fluctuation at Fig. 5 A-C and B-C. Figure 6 shows the local impedance of the test system. The impedance in a bracket is for 3rd harmonics. Apparently we can see the series resonance of 3rd harmonics with capacitors and reactors of the test system.

$$j(\,6.0 + 8.1\,) \approx -j\,(15.\,1)$$

Harmonic current in laboratory and its elimination

When a converter is 12 phase composed with 6 phase connection, the ac current is expressed by the following equation,

$$\begin{aligned} i = \sqrt{2}\, I_1 \Big\{ & \cos \omega t + \frac{0.87}{11} \cos (11\omega t + \theta_{11}) \\ & + \frac{0.83}{13} \cos (13\omega t + \theta_{13}) \\ & + \frac{0.58}{23} \cos (23\omega t + \theta_{23}) \\ & + \frac{0.48}{25} \cos (25\omega t + \theta_{25}) + \cdots\cdots \Big\} \end{aligned}$$

Assuming the phase angle, α, and commutating angle, u, is 122° and 10° respectively.

Besides, a voltage distortion by harmonics is expressed by

$$\Delta Vn/E = \frac{I, \cdot X_{01} \cdot Rn \cdot Kn}{E} \times 100\ \%$$

where

X_{01} : impedance of power source

Rn : ratio of harmonic current of n-th order to fundamental wave

Kn : Calverly coefficient

E : voltage of fundamental wave

I : current of fundamental wave

For actual power supply for the magnet, the harmonic current and voltages have been estimated and given in Table 6.

Table 6. Calculated harmonic current and voltage distortion.

Harmonic order	Harmonic current in amperes, I_n	Voltage distortion by harmonics in %, $\Delta V_n/E$
11	12.9	2.70
13	10.4	2.58
23	4.1	1.80
25	2.9	1.40

The value listed exceeds the permissible limit described. To reduce the harmonic currents to desired levels, it needs filters.

On the other hand, the flicker suppressor itself generates the harmonic current.

The whole system of laboratory is shown in Fig. 7.

In the power system, we have three power banks for magnets of main ring, booster and bubble chamber.

The capacity and impedance of transformers are summarized in Table 7.

Table 7. Capacity and impedance of transformers.

SYMBOL	Rating	Reactance
T_1, T_2, T_3	12 MVA 66 kV/6.6 kV	7.5%
T_{1A}, T_{1B}	12.5MVA 6.6kV/3.61kV	> 5 %
T_{1C}	8.8MVA 6.6kV/1.84kV	> 5 %
T_{3A}	2.75MVA 6.6kV/300V	~ 4 %

The generated harmonic current from TQC, magnet converter set, transformers, bubble chamber converter set and rectifier for beam lines are calculated and listed in Table 8.

Table 8. Estimated harmonic current in amperes.

ORDER	No. 1 bank			No. 2 bank		No. 3 bank			Permissible value
	transformers	power-supply	TQC	transformers	rectifier	transformers	bubble-chamber	converter	
2							66		87.5
3		39					4		58
4							38		44
5	7.9	39	160	5.3	8.8	5.3	14	17	35
6							17		29
7	2.6	10	115	1.8	6.3	1.8	20	12	25
8							15		22
9							17		19.5
10							9		17.5
11		173	32.8		4.0		9	30	15.9
12							1		14.6
13		145	30		3.4		7	25	13.5
14							6		12.5
15							2		11.7
16							5		11.0
17		11	20		2.6		5	4	10.3
18							4		9.7
19		9	15.4		2.3		4	4	9.2

The most right-hand column is the acceptable limited value of the harmonic current to giving the voltage distortion of 0.5 % at 66 kV network.

In the calculation and designing the filters, the following is considered:

(1) Target value of the minimum voltage distortion by harmonics on 66 kV is 0.5 % for each order of harmonics.
(2) Accounting the impedance change of the public power line in future, a safety factor 1.5 is introduced to above value.
(3) By the precise calculation and investigation on public power network (Tsuchiura line of Tokyo Power Company), (not reported here), no resonance was observed on the local grid covering a region extending 40 km.
(4) The short circuit capacity at connecting point is assumed to be 600 MVA and for harmonics, it is assumed that the impedance is linear, in other words, pure reactive. The allowed harmonic current (I_n) at 66 kV buss is

$$D_n = \frac{I_n\ (\mathrm{MVA})}{600\,(\mathrm{MVA})} \times n \times 100 \leq \frac{0.5}{1.5}\ (\%)$$

$$I_n \leq 2/n\ (\mathrm{MVA})$$

At 6.6 kV

$$I_n \leq 2/n = \frac{2\ (\mathrm{MVA})}{n \times 6.6\ \mathrm{kV} \times \sqrt{3}} = 175/n\ \ (\mathrm{A})$$

With the calculation based on above criteria, the system of the filters for 3 banks of power system is proposed as follows.

Table 9. Capacity of filters

Harmonic order	No. 1 bank	No. 3 bank
2nd		3 MVA
3rd	2 MVA	
5th	4 MVA	2 MVA
7th	4 MVA	
higher than 11th	10 MVA	2 MVA
total	20 MVA	7 MVA

More detailed report is not the purpose of the paper and will be reported elsewhere.

The most undesirable result is the overloading of power factor correction capacitors. The reactive power to be corrected was 14-19 MVar. We will prepare in total 20 MVA power of filters. Therefore we must prepare another reactors to correct the over compensation capacitors.

Conclusion

The preliminary test for the static power supply for the Japanese proton synchrotron demonstrates the feasibility of the thyristor control of the reactive power of the cyclo-converter. Technical difficulties have been overcome and the cost estimation has shown an economical merit in the considered system. The actual system has been designed with meeting requirements for the accelerator and also the available power system. The detailed computer analysis has been adopted. to the resonance problems which are regarded as the most serious effect to other consumers, as a result, that the power factor correcting capacitors are overloaded. It has become clear that the generated harmonic currents penetrate deeply into the peripheral region apart from 40 km in distance from the substation, but any resonance and any abnormal network disturbance were not found in every point considered. The capacitors for improving power factors were possible to be served as the filter for harmonics with slight amount of additive capacitors and reactors.

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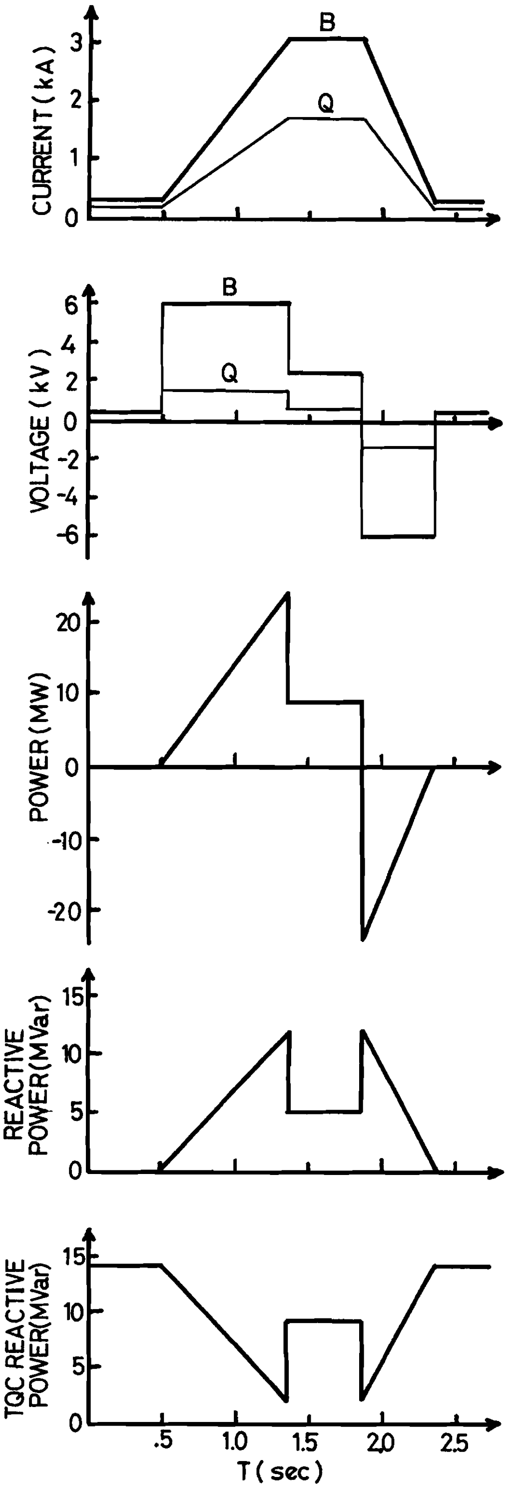

Fig. 1. Magnet current, voltage and power quantities of Japanese Proton Synchrotron.

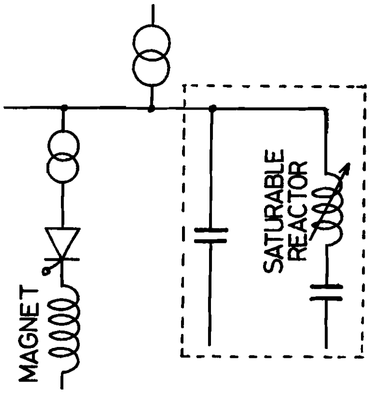

Fig. 2. Flicker suppressor with saturable reactor and shunt capacitor.

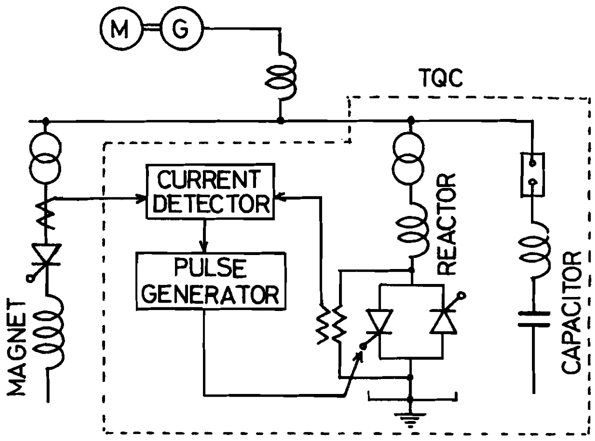

Fig. 3. System of testing set.

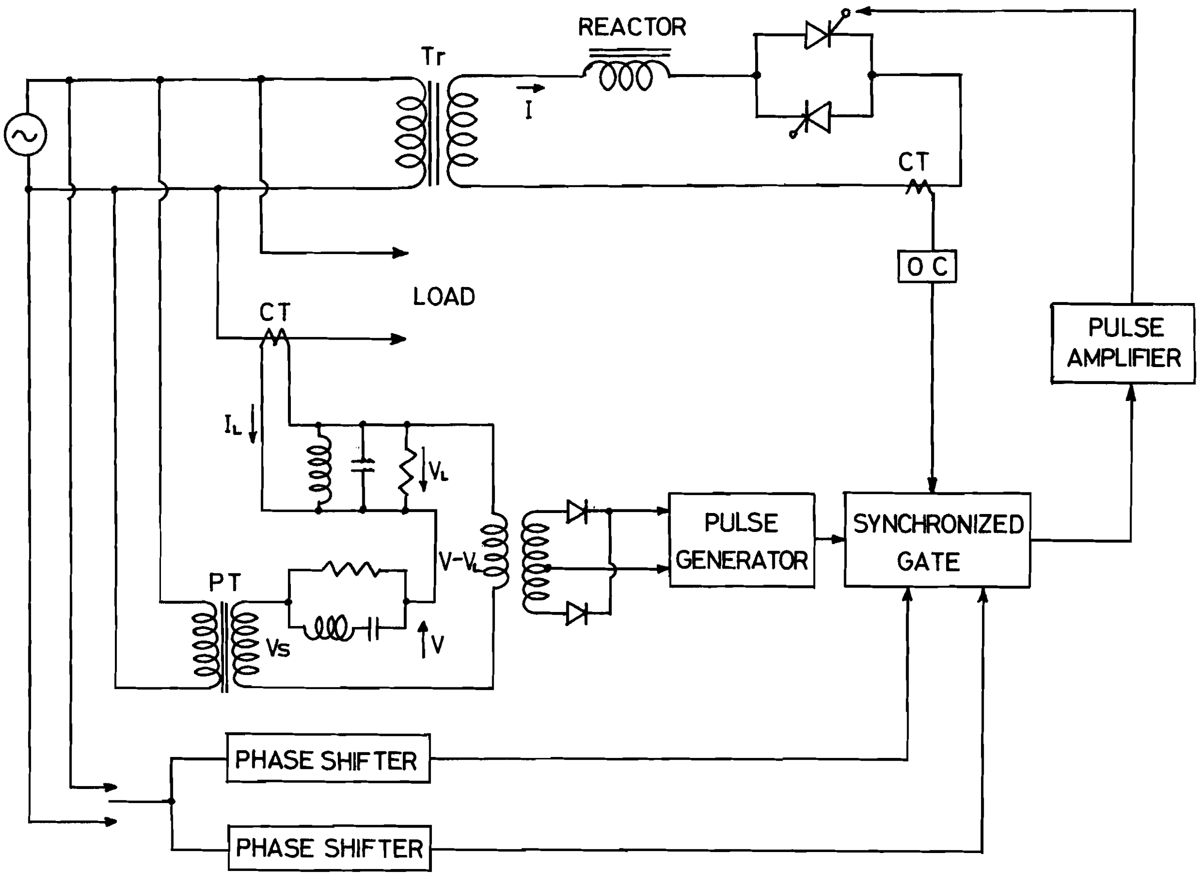

Fig. 4 A. Block diagram of TQC.

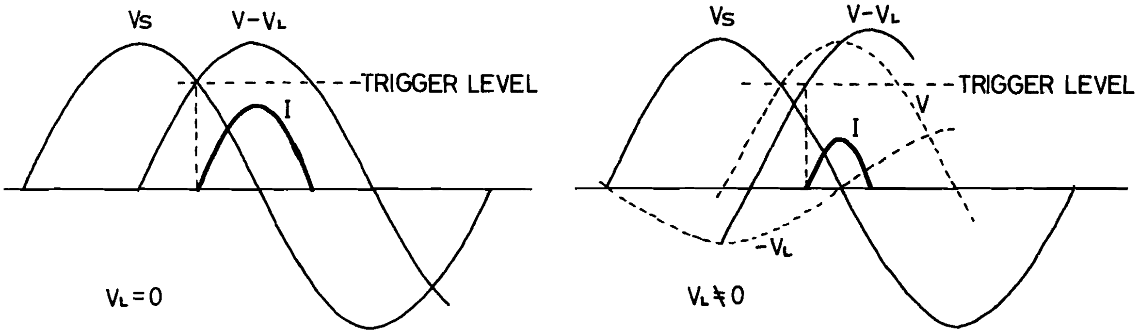

Fig. 4 B. Phase diagram of control in TQC.

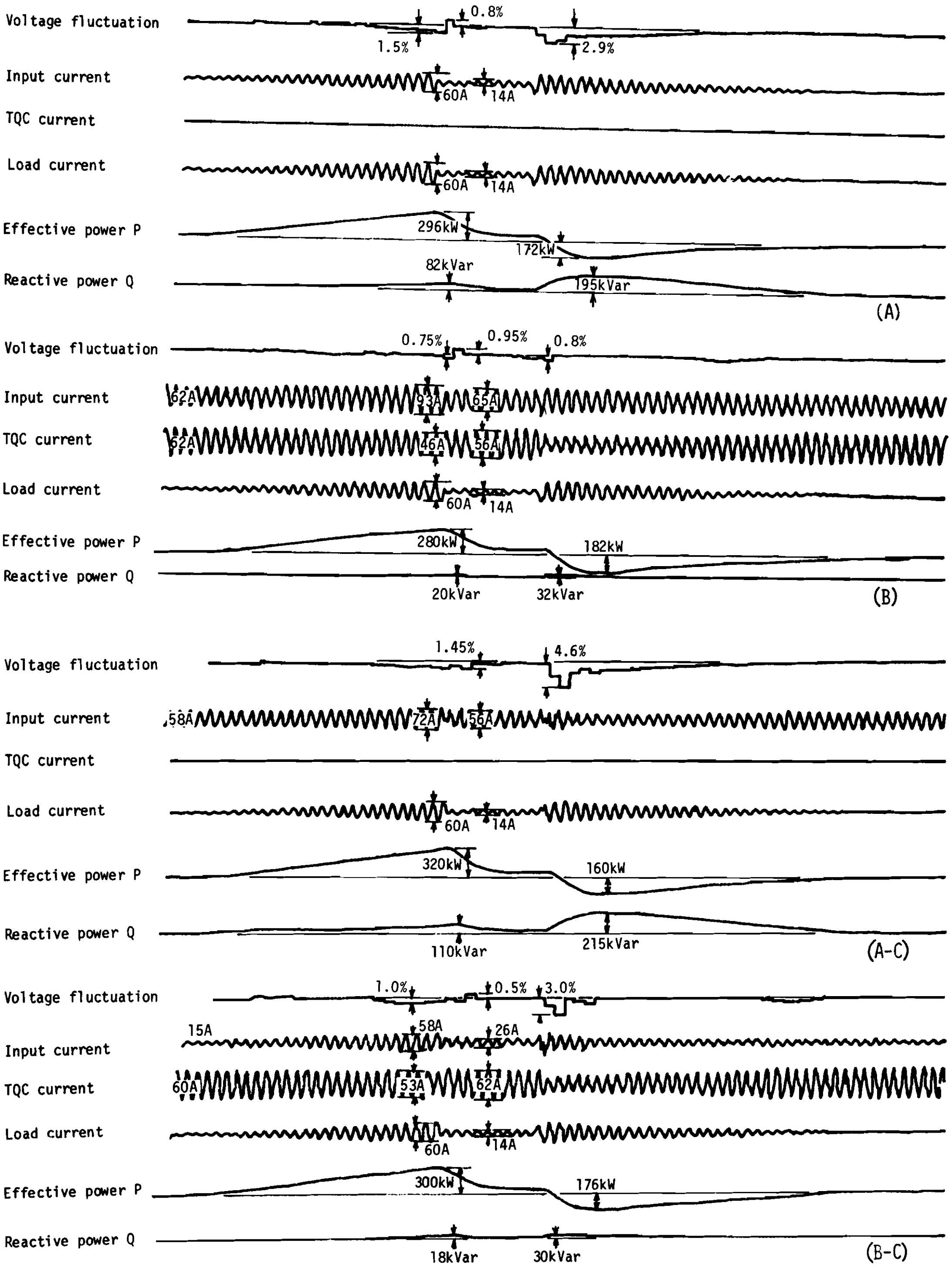

Fig. 5 Induced voltage fluctuations by fluctuated power and the effect of TQC.

A : without TQC
B : with TQC
A-C: without TQC and with power factor improving capacitor
B-C: with TQC and capacitor

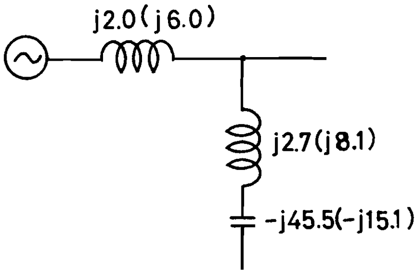

Fig. 6. Local impedance of test system.

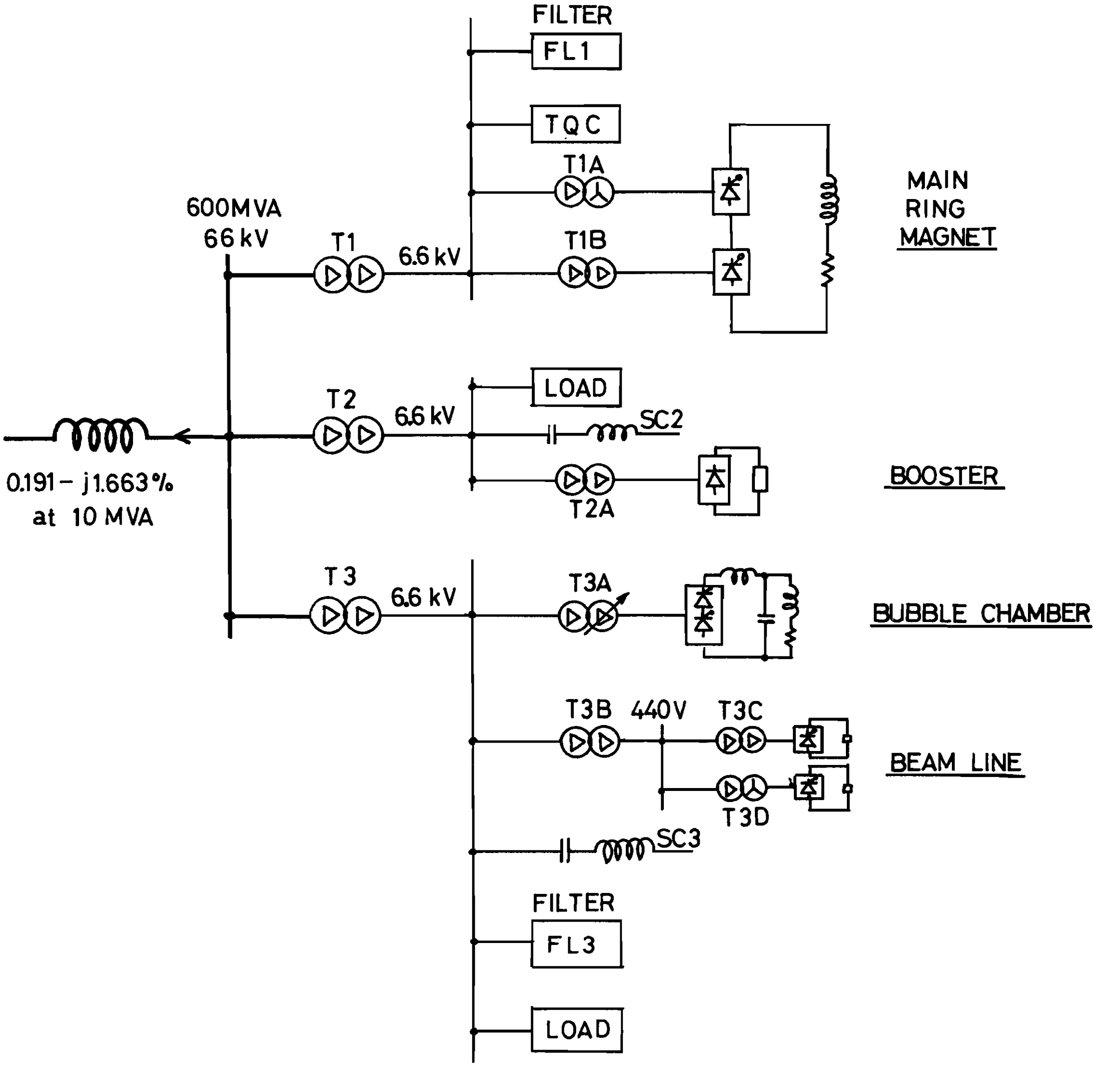

Fig. 7. Proposed power system of laboratory.