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Analysis of Crowbar Action of High Voltage DC Power Supply In the LHD ICRF System

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ABSTRACT

Ion Cyclotron Range of Frequency (ICRF) heating will be applied to the Large Helical Device (LHD) at the 2nd experimental campaign in 1998. The LHD ICRF system is characterised by its high power (up to 12MW at final stage) and steady state operation for more than 30 minutes. One of the main R&D items was a high power and steady state transmitter. The RF transmitter system having a wide frequency range from 25 to 95 MHz was designed and fabricated. This report describes the analysis of the DC power supply that contains the crowbar circuit protecting the tetrode from the arcing inside the tube. The DC power supply of the transmitter is fed from the commercial AC electric line which also supply the power to the LHD helical and poloidal coil power supplies. The voltage drop of the commercial line when the ICRF crowbar action happened is the serious problem for all experimental system. This paper analyses the crowbar effect on the commercial line with and without leakage transformer between the step-up transformer of transmitter and the commercial line.

Key words:
LHD, ICRF heating, Transmitter, DC power supply, Transformer

[1] Introduction

Ion Cyclotron Range of Frequency (ICRF) heating system has been prepared to apply for the ECH plasma on Large Helical Device (LHD) at the 2nd experimental campaign in 1998. The ICRF system is characterised by its high power (up to 12MW) and steady state operation (30 minutes). For which the research and development have started since 1990. The LHD is a helical device (with a major radius of 3.9m and a plasma minor radius of 0.6m) with super-conducting coil windings (l=2, m=10) and the main physical purpose is to investigate currentless and disruption-free steady state plasma. The research and development for ICRF heating has been carried out intensively in recent years. A high RF power transmission system was developed for the steady state ICRF heating, which consists of stub tuners, a ceramic feedthrough. In addition, an RF transmitter system with a wide frequency range, from 25 to 95MHz was designed and fabricated. The steady state operation was already achieved for 5,000 seconds at the output RF power of 1.6 MW in 50 MHz by furnishing the strong cooling system and by finding a low impedance mode to reduce a screen grid current and out-gassing in the tetrode tube.

The most weak and breakable part in the transmitter is the tetrode of the final amplifier and at the same time it is the most costly in the transmitter. To protect the tube against the serious damage from the breakdown in the tube, there is a crowbar circuit that makes the shorted circuit through the iginitron tube between the DC power supply and the tetrode. The crowbar circuit is effective to protect the tetrode but this dead short of the secondary circuit of the DC power supply may cause the large voltage drop on the commercial AC electric line. In the LHD experimental site, this voltage drop causes the many troubles in other experimental devices. To suppress the large voltage drop of the AC line, the leakage transformer was introduced. In the following sections, the effect of the leakage transformer is estimated in this report and compared with the test.

[2] Estimation of voltage drop on high power transformer system

The voltage drop on the commercial AC power line is estimated in several cases. To prevent the serious tetrode damage from the flashover inside the tube, the crowbar circuits are inserted between the main transformer of 20 MVA and the ICRF transformer of 5.5 MVA(for #1 and #2 transmitter) and transformer of 3.55 MVA(for #3 and #4 transmitter). When the crowbar action is occurred, a large voltage drop on the primary AC line was observed. To reduce the primary voltage drop, the insertion of the leakage transformer was considered. In the following section, the voltage drop in several cases (at the normal RF load or at the crowbar action, with and without leakage transformer) are calculated. Some of the results are compared with the experimental results and the coincidence was fairly good.

A complex simulation is usually needed for the calculation of voltage drop for a multi-phase power supply system which consist of transformers, rectifier and load. In this paragraph, we will provide a set of simplified formula obtained from the equivalent circuit. With these formula we can calculate the voltage drops and crowbar current of the system. We can also use this model during design of power system.

2.1 Case of two transformers series

We can simplify a two three-phase transformers series circuit as to Fig.1a. If Z_i is for impedance of the i-th transformer, we can get the equivalent circuit of the transformer impedance series as Fig.1b and Fig.1c. Derivation of the formula for general case of n-transformer is given in appendix-A. It is noted that the line impedance is not included.

From Fig.1b, we can write out following formula.

$$Z = Z_1 + Z_2 + Z_L \tag{1}$$

$$V_1 = IZ = I(Z_1 + Z_2 + Z_L) \tag{2}$$

$$V_2 = I(Z_2 + Z_L) = \frac{Z_1 + Z_2}{Z_1 + Z_2 + Z_L} V_1 \tag{3}$$

$$V_L = IZ_L \tag{4}$$

Where V and I are phasor and all Z is a vector.

$$Z = R + jX = |Z| \angle \vartheta \tag{5}$$

$$\vartheta = \mathrm{atan}(X/R) \tag{6}$$

1) Calculation of voltage drop of V_2 (et Vac) with load

$$\frac{|V_1| - |V_2|}{V_1} = 1 - \frac{|V_2|}{|V_1|} = 1 - \left| \frac{Z_2 + Z_L}{Z_1 + Z_2 + Z_L} \right| \tag{7}$$

Let $Z_L = Z_{H2}$, Z_{H2} is a rated load impedance, and formula (7) become

$$\frac{|V_1| - |V_2|}{|V_1|} = 1 - \left| \frac{1 + \%Z_2}{1 + \%Z_2 + k\%Z_1} \right| \tag{8}$$

where $k = Z_{H1}/Z_{H2} = W_{H2}/W_{H1}$ (9)

Z_{H1}, Z_{H2}, W_{H1} and W_{H2} are rated load impedance and rated transformer capacity of primary and secondary sides respectively.

2) Calculation of voltage drop of V_2 (et Vac) with shorted load (crowbar case)

$$\%V = 1 - \left| \frac{V_2}{V_1} \right| = 1 - \left| \frac{Z_2}{Z_1 + Z_2} \right| \tag{10}$$

Normalising the impedance referring to Z_{H2} rated load impedance

$$\left| \frac{Z_2}{Z_1 + Z_2} \right| = \left| \frac{\%Z_2}{\%Z_2 + \%Z_1 \cdot k} \right| \tag{11}$$

So,

$$\frac{\Delta V}{V_1} = \frac{|V_1| - |V_2|}{|V_1|} = 1 - \left| \frac{\%Z_2}{\%Z_2 + k \cdot \%Z_1} \right| \tag{12}$$

Where k is same as one of (9)

3) Estimation of ratio of crowbar current to rated one

We can use following formula to estimate a ratio of crowbar current to rated one in line.

$$Ic/I_{HL} = \left| \frac{Z_1 + Z_2 + Z_{HL}}{Z_1 + Z_2} \right| = \left| \frac{k\%Z_1 + \%Z_2 + 1}{k\%Z_1 + \%Z_2} \right| \tag{13}$$

$$I_{HL} = V_{H2}/Z_{H2} = W_{H2}/V_{H2} \tag{14}$$

I_{HL} and Z_{HL} are rated load current and impedance.

Defining k_{Ic} as a ratio of crowbar current to rated one in line

$$k_{Ic} \equiv I_c/I_{HL} \tag{15}$$

It means crowbar current are k_{Ic} times of rated one in line.

2.2 Case of a leakage inductor inserted between two transformers series

Similar to the case of two transformer series, we can take an equivalent circuit of three three-phase transformer series circuit as Fig.2 .a, b, and c.

1) Calculation of voltage drop of V_2 (et V_{ac}) with load

$$\frac{|V_2|}{|V_1|}=\left|\frac{Z_2+Z_3+Z_{LH}}{Z_1+Z_2+Z_3+Z_{LH}}\right|=\left|\frac{1+\%Z_3+k_2\%Z_2}{1+\%Z_3+k_1\%Z_1+k_2\%Z_2}\right| \quad (16)$$

Where $k_1=Z_{H1}/Z_{H3}=W_{H3}/W_{H1}$, $k_2=Z_{H1}/Z_{H3}=W_{H3}/W_{H2}$ (17)

2) Calculation of voltage drop of V_2 (et Vac) with load shorted (crowbar case)

$$\frac{|V_2|}{|V_1|}=\left|\frac{k_2\%Z_2+\%Z_3}{k_1\%Z_1+k_2\%Z_2+\%Z_3}\right| \quad (18)$$

$$\frac{|V_3|}{|V_1|}=\left|\frac{Z_3}{Z_1+Z_2+Z_3}\right|=\left|\frac{\%Z_3}{k_1\%Z_1+k_2\%Z_2+\%Z_3}\right| \quad (19)$$

3) Reduction ratio of crowbar current with and without leakage inductor cases

Let I_{1c}, I_{2c} for crowbar currents of with and without leakage inductance separately,

$$\frac{|I_{1c}|}{|I_{2c}|}=\left|\frac{Z_1+Z_3}{Z_1+Z_2+Z_3}\right|=\left|\frac{k_1\%Z_1+\%Z_3}{k_1\%Z_1+k_2\%Z_2+\%Z_3}\right| \quad (20)$$

2.3 Calculation of voltage drop for the transformer system of #1 and #2 transmitters

For calculation of voltage drop in the transformer system of #1 and #2 transmitters with the formula given in the paragraph above, the rated power capability and percent impedance of the transformers of #1 and #2 transmitters are given as follows.

	Trans.1	Leakage Trans	Trans.2	DC load
W_H	20MVA	7.4 MVA	5.5MVA	2-3 MW
%R	3.3%	3.4%	0.9%	
%X	j16.2%	j30%	j 7.0%[9.0%]	

$k_1=Z_{H1}/Z_L=W_{HL}/W_{H1}$
$k_2=Z_{H2}/Z_L=W_{HL}/W_{H2}$
$k_3=Z_{H3}/Z_L=W_{HL}/W_{H3}$

1) With load but no leakage transformer

We can calculate the voltage drop using the data given above with the formula (8)

$$\frac{|V_1|-|V_2|}{|V_1|}=1-\left|\frac{1+\%Z_2}{1+\%Z_2+k_1\%Z_1}\right|=1.3\%$$

and

$$\frac{|V_{load}|}{|V_1|}=\left|\frac{Z_L}{Z_1+Z_2+Z_L}\right|=\left|\frac{1}{1+k_1\%Z_1+k_2\%Z_2}\right|=0.973$$

$\Delta V_{load}/V_1=2.7\%$
so
$\Delta V_L/V_1=1.3\%$
$\Delta V_{trans2}/V_{trans2}=1.4\%$
$\Delta V_{DC}/V_{DC}=(6.7\sim7.7)\%$ (in DC side, $W_{DC}=2.0\sim3.5$MW)

2) Calculation of voltage drop and estimation of the ratio of crowbar current to rated one in shorted load (crowbar case without leakage transformer)

With the data given above and by using formula (9) and (12), the results are

$$\%V=1-\left|\frac{V_2}{V_1}\right|=1-\left|\frac{\%Z_2}{\%Z_2+k_1\%Z_1}\right|=1-0.61=39\%$$

(if k=0.275)

= 46% (if k=0.37)
or, $V_2=0.54V1$ (k=0.37)
$V_2=0.61V1$ (k=0.275)

The experiment data is 0.57. It is more liable to take the transformer capacity as 5.5MVA

From formula (13) and (15),we obtain

$$I_c/I_{HL}=\left|\frac{k_1\%Z_1+\%Z_2+1}{k_1\%Z_1+\%Z_2}\right|=0.94$$

I_{HL}=5.5MVA/6.6kV=833A

So, a value of estimated crowbar current in the line is to be Ic =9.4×833=8.4kA, the percent error is 6.8%.

It is noted that reactance X of a transformer may be changed during shorted state, any linear simulation is approximately too.

3) Calculation of voltage drop with leakage transformer and load

Using the formula (13), (14) with the data given above and referring to fig.3.a, we get

$$\frac{|V_2|}{|V_1|} = \left| \frac{1 + \%Z_3 + k_2\%Z_2}{1 + \%Z_3 + k_1\%Z_1 + k_2\%Z_2} \right| = 0.98$$

$|V_3| / |V_1| = 0.923$

Where k_1=0.275, k_2=0.743.

4) Calculation of voltage drop with leakage transformer in load shorted case

(crowbar action)

From formula (18) and (19), we can obtain

$$\left|\frac{V_2}{V_1}\right| = \left| \frac{k_2\%Z_2 + \%Z_3}{k_1\%Z_1 + k_2\%Z_2 + \%Z_3} \right| = 87\%$$

$$\frac{|V_3|}{|V_1|} = \left| \frac{\%Z_3}{k_1\%Z_1 + k_2\%Z_2 + \%Z_3} \right| = 21\%$$

So,

$\Delta V_2/V_1$=13%

$\Delta V_3/V_1$=79%

For getting the reduction ratio of crowbar current with and without leakage transformer cases, we use formula (20) and obtain

$$\frac{|I_{1c}|}{|I_{2c}|} = \left| \frac{k_1\%Z_1 + \%Z_3}{k_1\%Z_1 + k_2\%Z_2 + \%Z_3} \right| = 0.34$$

The results obtained in section 31-3-3 are listed in Table 1 compared with test results More details of the results are in the Table 2.

2.4 Calculation of voltage drop for the transformer system of #3 and #4 transmitters

The power capability and percent impedance of the transformers of #3 and #4 are given as follows.

	Trans.1	Leakage Trans	Trans.2	DC load
W_H	20MVA	7.4 MVA	3.55MVA	1.5-2MW
%R	3.3%	3.4%	1.52%	
%X	j16.2%	j30%	j6.1%	

$k_1 = Z_{H1}/Z_L = W_{HL}/W_{H1}$

$k_2 = Z_{H2}/Z_L = W_{HL}/W_{H2}$

1) With load but no leakage transformer

We can calculate the voltage drop using the data given above with the formula (8)

$$\frac{|V_1| - |V_2|}{|V_1|} = 1 - \left| \frac{1 + \%Z_2}{1 + \%Z_2 + k_1\%Z_1} \right| = 0.74\%$$

And

$$\frac{|V_{load}|}{|V_1|} = \left| \frac{Z_L}{Z_1 + Z_2 + Z_L} \right| = \left| \frac{1}{1 + k_1\%Z_1 + k_2\%Z_2} \right| = 0.976$$

So

$\Delta V_L/V_1$=2.4%

$\Delta V_{trans2}/V_{trans2}$ =1.7%

$\Delta V_{DC}/V_{DC}$=(5.2~6.4)% (in DC side, W_{DC}=1.5-2.0MW)

2) Calculation of voltage drop and estimation of the ratio of crowbar current to rated one in shorted load (crowbar case without leakage transformer)

From formula (12), we obtain

$$\%V = 1 - \left|\frac{V_2}{V_1}\right| = 1 - \left| \frac{\%Z_2}{\%Z_2 + k_1\%Z_1} \right| = 1 - 0.6339 = 36.6\%$$

From formula (13), we obtain

$$I_c/I_{HL} = \left| \frac{k_1\%Z_1 + \%Z_2 + 1}{k_1\%Z_1 + \%Z_2} \right| = 11.1$$

I_{HL}=3.55MVA/6.6kV=538A

So the crowbar current in the line Ic =11.1×538=5972A

We note that the voltage drop of #3 and #4 transmitter is just a little less than one in 5.5MVA transformer of #1 and #2 transmitters. And, more important is that the crowbar current ratio is larger than 11. The crowbar current may be larger than the 3.55MVA transformer allows.

3) Calculation of voltage drop with leakage transformer in load shorted case (crowbar action)

From formula (15) we can obtain

$$\left|\frac{V_2}{V_1}\right| = \left|\frac{k_2\%Z_2 + \%Z_3}{k_1\%Z_1 + k_2\%Z_2 + \%Z_3}\right| = 87.6\%$$

So,

$\Delta V_2/V_1$=12.4%

For getting the reduction ratio of crowbar current with and without leakage transformer cases, we use formula (17) and obtain

$$\frac{|I_{1c}|}{|I_{2c}|} = \left|\frac{k_1\%Z_1 + \%Z_3}{k_1\%Z_1 + k_2\%Z_2 + \%Z_3}\right| = 0.39$$

So the crowbar current in the line will be I_{1c}=0.39×5972=2330A, it is still high level.

From the results calculated in this paragraph, we can conclude that a leakage transformer between the power transformers (or a resistor on the DC side) is necessary for the power supply system of #3 and #4, and the leakage transformer should be optimised for #3 and #4 proper. Another better approach is to use Flywheel Generator to provide the 3.55MVA transformer system.

We list the estimated results in Table- 3. There are more results of voltage drop for the transformer power system of #3and #4 in different case.

[3] Discussions

Through the calculation above we conclude as follows:

1) In the case of #1 and #2 transmitters, insertion of the leakage transformer will reduce the voltage drop below 15 %, which is the maximum allowed disturbance to the commercial line.

2) In the case of #3 and #4 transmitters, insertion of the same leakage transformer will not be enough. It should be optimised for them proper.

3) The same calculation method will be used for the case of insertion of resistances in the DC circuit.

4) It is mentioned that the voltage drop obtained here is not of transient calculation but of steady state calculation. Therefore it is rather overestimate if we take into consideration that the vacuum circuit breaker follows the crowbar switch to terminate the sequence.

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Table 1 Results for the transformer system of #1 and #2 compared with test results

	Estimation result	result of test
With load		
V2/V1	98%	
V3/V1	92%	
With action of crowbar		
V2/V1	87%	87.2% (on 9/11/98).
V3/V1	21%	
Reduction of crowbar current		
I_{1c}/I_{2c}	0.34	

Note: the leakage transformer is inserted.

Table 2. Detailed results of voltage drops on the transformers of #1 and #2

Without leakage transformer and with load

V_2/V_1=0.986 V_L/V_1=0.973 or $\Delta V_2/V_1$=1.4% $\Delta V_L/V_1$= 2.7%

$\Delta V_{tran1.}/V_{tran1.}$=1.4% (on Trans. 20MVA)

$\Delta V_{tran2.}/V_{tran2.}$=1.3% (on Trans. 5.5MVA)

$\Delta V_d/V_d$=6.7% (in DC side, including 3% line drop and ≈1% of DC side)

With leakage transformer and with load

V_2/V_1=0.98 V_3/V_1=0.923 V_L/V_1=0.913 or $\Delta V_2/V_1$=2% $\Delta V_3/V_1$=7.7% $\Delta V_L/V_1$=8.7%

$\Delta V_{tran.}/V_{tran.}$= 2%(Trans. of 20MVA)

$\Delta V_{tran2}/V_{tran2}$=5.7% (Leakage trans.)

$\Delta V_{tran3}/V_{tran3}$=1% (Trans. of 5.5MVA)

$\Delta V_d/V_d$=12.7%*.

* Note:

The DC side voltage drop $\Delta V_d/V_d$=12.7% include 3% line drop, 8.7% calculated from parameters and another ~1% of DC side.

Table 3. The voltage drops on the transformers for #3 and #4

Without leakage transformer and with load

V_2/V_1=0.9926 V_L/V_1=0.976 or $\Delta V_2/V_1$=0.74% $\Delta V_L/V_1$= 2.4%

$\Delta V_{tran1}./V_{tran1}.$=0.74% (on Trans.20MVA)

$\Delta V_{tran2}./V_{tran2}.$=1.7% (on Trans.3.55MVA)

$\Delta V_d/V_d$=5.2-6.4% (in DC side, including 3% line drop and ≈1% of DC side)

Without leakage transformer and in shorted circuit

V_2/V_1=0.6339 $\Delta V_2/V_1$=36.6%

$\Delta V_{tran1}./V_{tran1}.$=36.6% (on Trans.20MVA)

over-current factor Ic/I_{HL}=11.1

sorted current in line Ic=5972A

With leakage transformer and with load

V_2/V_1=0.989 V_3/V_1=0.956 V_L/V_1=0.940 or $\Delta V_2/V_1$=1.1% $\Delta V_3/V_1$=4.4% $\Delta V_L/V_1$=6.0%

$\Delta V_{tran}./V_{tran}.$= 1.1%(Trans. of 20MVA)

$\Delta V_{tran2}/V_{tran2}$=3.3% (Leakage trans.)

$\Delta V_{tran3}/V_{tran3}$=1.6% (Trans. of 5.5MVA)

$\Delta V_d/V_d$=10%.

With leakage transformer and in sorted case

V_2/V_1=0.876 V_3/V_1 =0.266 or $\Delta V_2/V_1$=12.4% $\Delta V_3/V_1$=73.4%

$\Delta V_{tran}./V_{tran}.$=12.4%(Trans. of 20MVA)

$\Delta V_{tran2}/V_{tran2}$=61% (Leakage trans.)

I_{1c}/I_{2c}=0.39 (Reduction of crowbar current)

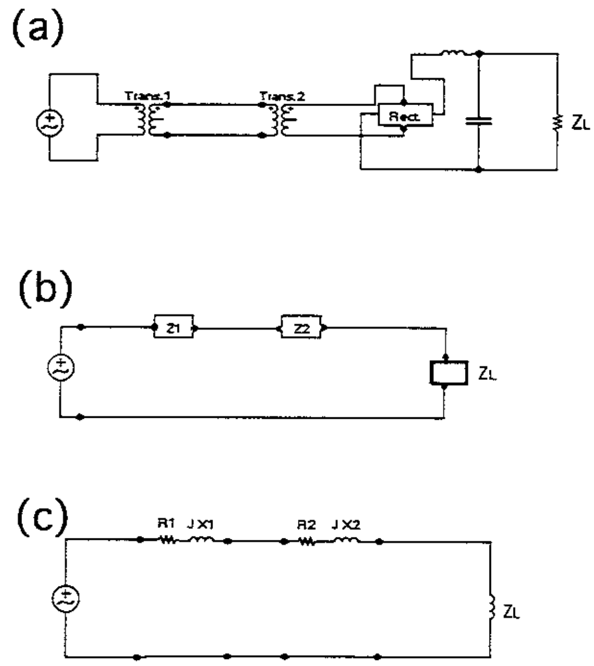

Fig.1. Equivalent circuit of two 3-phase transformers series

(a) Simplified circuit of two 3-phase transformers series

(b) & (c) Impedance Equivalent Circuit of the series transformers

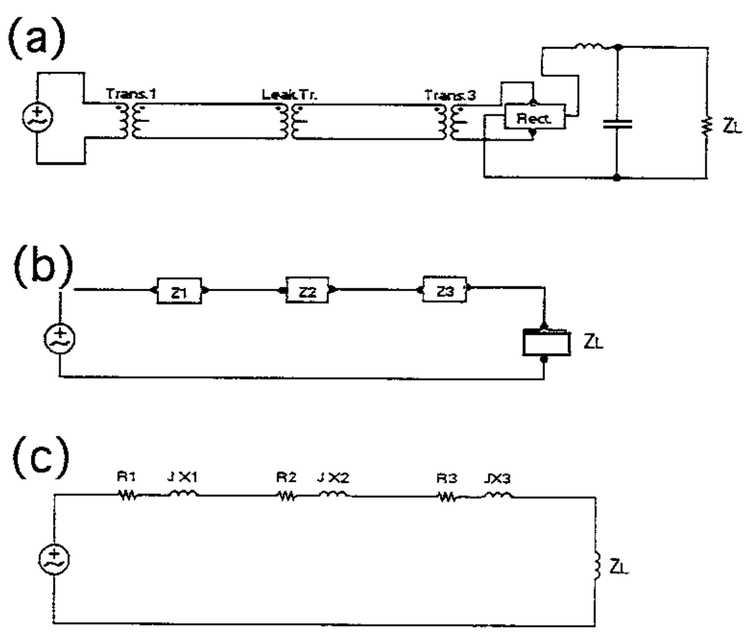

Fig.2. Equivalent circuit of three 3-phase transformers series

(a) Simplified circuit of three series 3-phase transformers

(b) & (c) Impedance Equivalent Circuit of the series transformers

Appendix A

Method of voltage drop calculation

The calculation procedure of voltage drop is derived in this appendix.

The equivalent circuit of a transformer is shown in Fig. A-1 with conventional notations for L, M, and r.

$$Z_1 = (L_1 - M)\omega j + r_1 \qquad (A-1)$$

and

$$Z_2 = (L_2 - M)\omega j + r_2 \qquad (A-2)$$

Here, Z_L is the load connected to the transformer . The impedance of the loaded transformer is easily obtained from inspection of Fig. A-1.

$$Z = \frac{V}{I} = Z_1 + \frac{1}{\frac{1}{M} + \frac{1}{Z_L + Z_2}} \qquad (A-3)$$

$$= Z_1 + \frac{M(Z_L + Z_2)}{(Z_2 + M) + Z_L} \qquad (A-4)$$

$$\approx \left(Z_1 + \frac{MZ_2}{Z_2 + M}\right) + \frac{M^2}{(Z_2 + M)^2} Z_L \qquad (A-5)$$

where following assumption was made:

$$|Z_L| < |Z_2 + M| \text{ and } |Z_L| < |Z_2| \qquad (A-6)$$

Substituting equations (A-1) and (A-2), eq. (A-5) is transformed as

$$Z = (L_1 - M)\omega j + r_1$$

$$+ \frac{M\omega j}{L_2 \omega j + r_2} \{(L_2 - M)\omega j + r_2\}$$

$$+ \frac{(M\omega j)^2}{(L_2 \omega j + r_2)^2} ZL \qquad (A-7)$$

$$\approx Z_{tr} + \tilde{Z}_L \qquad (A-8)$$

Here, $Z_{tr} \equiv X\omega j + R$ with

$$X \equiv \left(L_1 - \frac{M^2}{L_2}\right)\omega j, \; R \equiv r_1 + \left(\frac{M}{L_2}\right)^2 r_2,$$

$$\text{and } \tilde{Z}_L \equiv \frac{M_1^2}{L_2^2} Z_L \approx \frac{L_1}{L_2} Z_L \approx \left(\frac{V_1}{V_2}\right)^2 Z_L \approx \left(\frac{I_2}{I_1}\right)^2 Z_L \qquad (A-9)$$

Equation (A-8) suggest that the voltage drop associated with an insertion of a transformer is analyzed based on the equivalent circuit shown in Fig. A-2.

Fig. 2 suggests, in the case that N transformers are connected in series as shown in Fig. 3, that the loaded impedance at the primary side of the n-th transformer is expressed by a recurrence formula

$$Z(n) = Z_n + \left(\frac{L_{n,p}}{L_{n,s}}\right) Z(n-1) = Z_n + \left(\frac{I_{n,s}}{I_{n,p}}\right)^2 Z(n-1) \qquad (A-10)$$

So far, the subscripts 1 and 2 have been used to designate primary and secondary sides, respectively. Henceforth, p and s are used in their places and subscript n indicates that the quantity is characteristic to n-th transformer. We define percent impedance by

$$\%Z_n \equiv \frac{Z_n}{Z_{B,n}}, \qquad (A-11)$$

with

$$Z_{B,n} \equiv \frac{V_{B,n}^2}{W_{B,n}} = \frac{W_{B,n}}{I_{B,n}^2} \qquad (A-12)$$

where $V_{B,n}$ and $W_{B,n}$ are, standard voltage and standard power of n-th transformer. Using eqs (A-10) - (A-12), we find

$$\%Z(N)=\frac{Z(N)}{Z_{B,N}}=1+\left(\frac{V_{B,N,p}}{V_{B,N,s}}\right)^2\frac{Z_{B,N-1}}{Z_{B,N}}\%Z(N-1)$$

$$1+\left(\frac{V_{B,N,p}}{V_{B,N-1,p}}\right)^2\frac{Z_{B,N-1}}{Z_{B,N}}\%Z(N-1)=\%Z(N)+\frac{W_{B,N}}{W_{B,N-1}}\%Z(N-1) \qquad (A-13)$$

By using the recurrence formula , the following result is obtained.

$$\%Z(N)=\%Z_N+\frac{W_{B,N}}{W_{B,N-1}}\%Z_{N-1}+\frac{W_{B,N}}{W_{B,N-2}}\%Z_{N-2}$$

$$+ \quad +\frac{W_{B,N}}{W_{B,1}}\%Z(n=1) \qquad (A-14)$$

Specifically, for n=1, we find from inspection of Fig.(A-3)

$$W_{B,dc}=(I_{B,dc})^2 Z_{B,L} \qquad (A-15)$$

$$W_{B,P}=(I_{B,1,P})^2 Z_{B,1,P} \qquad (A-16)$$

which gives

$$\left(\frac{I_{B,1,dc}}{I_{B,1,P}}\right)^2=\left(\frac{Z_{B,1,P}}{Z_{B,dc}}\right)\frac{W_{B,dc}}{W_{B,1,P}}=\left(\frac{Z_{B,1,P}}{Z_{B,dc}}\right) \qquad (A-17)$$

Substituting eq (17) into eq(10), we obtain

$$Z(n=1)=Z_1+\left(\frac{I_{B,DC}}{I_{B,1,p}}\right)^2 Z_L=Z_1+\left(\frac{W_{B,DC}}{W_{B,1,P}}\right)\left(\frac{Z_{B,1,P}}{Z_{B,DC}}\right)Z_L$$

$$=Z_1+Z_{B,1,P}\left(\frac{Z_L}{Z_{B,DC}}\right) \qquad (A-18)$$

where we have put $W_{B,1,p}=W_{B,1,s}=W_{B,1}=W_{B,DC}$ and shall observe it.

Finally, by dividing eq(A-18) by $Z_{B,1,p}$, the following expression is obtained:

$$\%Z(n=1)=\%Z_1+\%Z_L \qquad (A-19)$$

where,

$$\%Z_L=Z_L/Z_{B,L}=Z_L/\left(V_{B,DC}^2/W_{B,1}\right) \qquad (A-20)$$

As an special case of application of the formula , the voltage drop at the primary side of the N-1 th transformer is given by

$$\frac{\delta V}{V}=1-\left|\frac{(I_{N,s}/I_{N,p})^2 Z(N-1)}{Z(N)}\right|=1-\left|\frac{(I_{N,s}/I_{N,p})^2 Z_{B,N-1}\%Z(N-1)}{Z_{B,N}\%Z(N)}\right|$$

$$=1-\left|\frac{(V_{B,N,p}/V_{B,N,s})^2(W_{B,N-1})Z_{B,N-1}(1+\sum_{n=1}^{n=N-1}\frac{W_{B,L}}{W_{B,n}}\%Z(n))}{(W_{B,N})Z_{B,N}(1+\sum_{n=1}^{n=N}\frac{W_{B,L}}{W_{B,n}}\%Z(n))}\right|=1-\left|\frac{(1+\sum_{n=1}^{n=N-1}\frac{W_L}{W_n}\%Z(n))}{(1+\sum_{n=1}^{n=N}\frac{W_{B,L}}{W_{B,n}}\%Z(n))}\right| \quad (A-21)$$

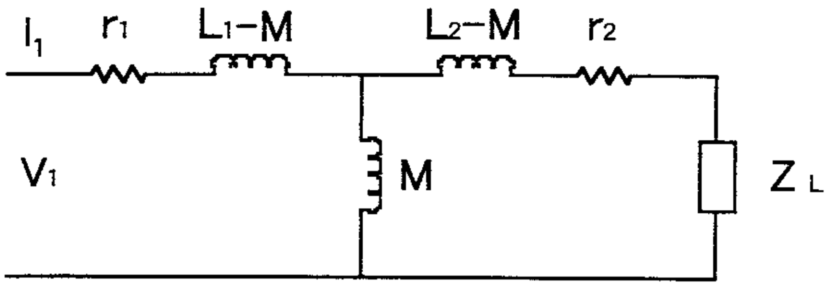

Fig.A-1 Equivalent circuit including a transformer and a load

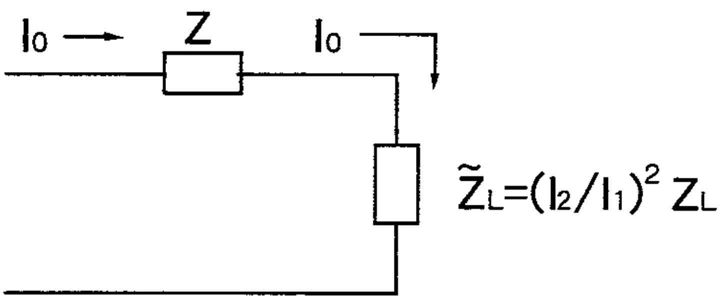

Fig.A-2 Simplified equivalent circuit corresponding to the circuit in Fig.A-1

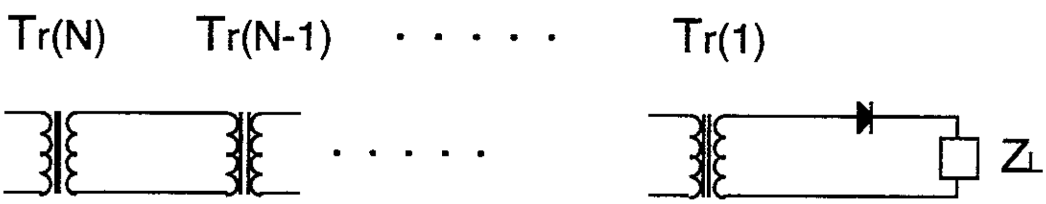

Fig.A-3 A circuit including N-transfomers in series

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