

Reduction Method of High Harmonic Currents on the AC Side of the Diode Rectifier Circuits in the AC Electric Railways

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Abstract—We propose the method which is able to suppress the generation of the high harmonic currents on the AC side of the diode rectifier circuits in the AC electric railways by connecting the CR series circuit in parallel with the load on the DC side. From the experimental and theoretical results, it is confirmed that this method produces the desirable effect for the reduction of high harmonics and the improvement of the power characteristics.

I. INTRODUCTION

In the AC electric railways, the single phase rectifier circuits placed in the car generate high harmonic currents on the AC side. The lower order components of the generated harmonics may cause breakdown and overheating of the power source transformer and the Power Factor improvement capacitor etc.. Also, the higher order components cause inductive interference to neighboring communication lines and the train control information etc..

As a countermeasure, the AC filter to reduce harmonic currents on the AC side has been adopted [1][2], but it does not have much effect [3][4]. Also, problems [5] such as increase in the size of capacitor kVA accompanied by fundamental harmonic current inflow arise.

Then, we propose the new reduction method [6][7][8] of the high harmonic currents in the car using the diode rectifier circuits. It is able to suppress the generation of the high harmonic currents on the AC side by connecting the CR series circuit in parallel with the load on the DC side of the rectifier circuits.

In this paper, the theoretical analysis [9] of the single phase rectifier circuit adopted this method is presented. In this analysis, we separate into two operating modes and carry out the circuit analysis for each mode. Furthermore, we make calculations and experiments on the condition of electric railways, and then indicate the power characteristics and the reduction effects of high harmonic currents. And, it is clarified that adopting this method to the car using the diode rectifier circuits produces the desirable effects for reduction of the high harmonics and the power characteristics.

II. BASIC CONCEPTION OF THE REDUCTION METHOD

The equivalent circuit configuration of a tap control car is shown with a solid line in Fig.1. In this circuit, X_p and R_p show the resultant reactance (inductance L_p) and the resistance on the AC power source side. X_d and R_d show the

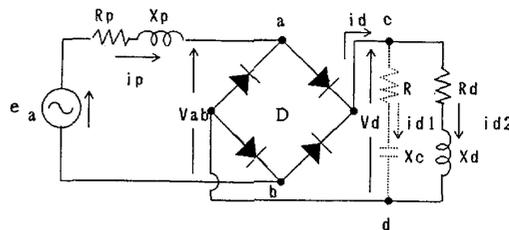


Fig.1. Equivalent circuit of electric railway applied this method.

resultant reactance (inductance L_d) and resistance of the DC series motor and smoothing reactor etc..

Generally, the equivalent circuit on the DC motor side is expressed in an alternating equivalent resistance R_t , reactance X_d and a constant counter e.m.f E . In this analysis, we substitute a DC equivalent resistance R_e for a counter e.m.f E . Then, in Fig.1, R_d shows $R_t + R_e$. The influence of this treatment is discussed in the later chapter.

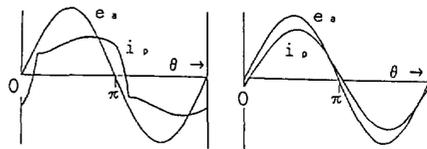
Fig.2(a) shows the voltage and current waveforms on the AC side of this circuit configuration. In this figure, AC side current i_p contains the high harmonics based on the inductive load.

Then, we propose the new method that the CR series circuit (shown a dotted line in Fig.1) is connected in parallel with the load on the DC side. Therefore, DC side circuit consists of the parallel circuit of the load and the CR series circuit. Then, if the relation of the circuit constants on the DC side can be maintained as follows

$$X_d X_c = R_d^2 = R^2 \quad (\text{constant resistance condition}), \quad (1)$$

impedance of the DC side can be considered to be a pure resistance.

Fig.2(b) shows the voltage and current waveforms on the AC side under the condition of the equation (1). The AC side



(a) General waveforms. (b) Waveforms applied this method.

Fig.2. Voltage and current waveforms on the AC side.

current i_p becomes a sine wave which does not contain the high harmonic components. Also, the AC side impedance has effect only on Power Factor and the current magnitude on the AC side.

Thus, when the load constant values are given, the most desirable values of the CR circuit for high harmonics reduction can be determined by the equation (1). But, in practice, the condition is not always satisfied for reason of the load fluctuation. In this case, the AC side impedance has an effect on the AC current waveform. Therefore, in the area that the equation (1) is not satisfied, the characteristics of high harmonics reduction and efficiency have to be investigated.

In order to carry out the above-mentioned investigation, analysis method of the rectifier circuit with the CR series circuit on the DC side is described in the next chapter.

III. ANALYSIS OF THE RECTIFIER CIRCUIT WITH THE CR SERIES CIRCUIT

In the rectifier circuit with the CR series circuit on the DC side, commutation condition can be divided into two modes in compliance with circuit constant conditions.

- (1) There is commutation state. (mode 1)
- (2) There is no commutation state. (mode 2)

And constant resistance condition is located in boundary of modes 1 and 2.

A. Analysis of mode 1

In the CR series circuit, when C is small or R is large in comparison with the CR constant values given by the eq.(1), there is commutation state.

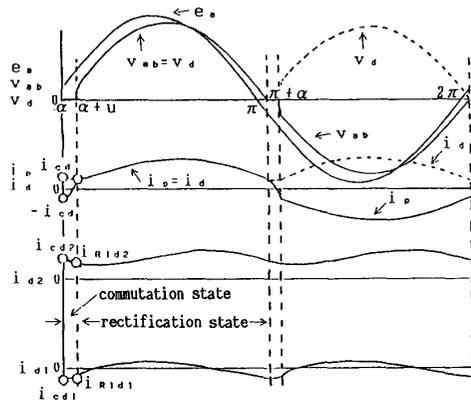


Fig.3. Voltage and current waveforms (mode 1).

Fig.3 shows the voltage and current waveforms in this condition. Each symbol corresponds to Fig.1. For the analysis of the circuit in Fig.1, commutation start angle α , the currents of each part in commutation and rectification states have to be calculated.

- (a) Commutation start angle α

Commutation start angle is rectification end phase in which terminal voltage of rectifier circuit becomes zero. Hereafter, v_{ab} and v_d in Fig.1 keep zero, because all rectifier elements are in short state. Hence, circuit equations are given in the following differential equations;

$$e_a - R_p i_p - X_p \frac{d i_p}{d \theta} = 0 \quad (2)$$

$$R i_{d1} + X_c \int i_{d1} d \theta = 0 \quad (3)$$

$$R_d i_{d2} + X_d \frac{d i_{d2}}{d \theta} = 0 \quad (4)$$

$$e_a = E_m \sin \theta \quad (5)$$

where each initial current at commutation start angle α is $i_p = -i_{cd}$, $i_{d1} = i_{cd1}$, $i_{d2} = i_{cd2}$ and $i_{cd} = i_{cd1} + i_{cd2}$. Therefore, the start angle α of commutation state is

$$\alpha = \sin^{-1} \left[\frac{\{X_p(X_c i_{cd1}/R + R_d i_{cd2}/X_d) - R_p(i_{cd1} + i_{cd2})\}}{E_m} \right] \quad (6)$$

- (b) Commutation state ($\alpha \leq \theta \leq \alpha + u$)

In the commutation state, the AC side circuit and the DC side circuit respectively behave as independent circuit, because the terminal voltages of rectifier circuit are in short state. By the solutions of the equations (2)~(5) each i is shown in the following equations;

$$i_p = \{E_m \sin(\theta - \phi_1)\} / Z_1 - \{i_{cd} + \{E_m \sin(\alpha - \phi_1)\} / Z_1\} \times \exp\{-R_p(\theta - \alpha)/X_p\} \quad (7)$$

$$i_{d2} = i_{cd2} \exp\{-R_d(\theta - \alpha)/X_d\} \quad (8)$$

$$i_{d1} = i_{cd1} \exp\{-X_c(\theta - \alpha)/R\} \quad (9)$$

$$i_d = i_{d1} + i_{d2} \quad (10)$$

where $Z_1 = (R_p^2 + X_p^2)^{1/2}$, $\phi_1 = \tan^{-1}(X_p/R_p)$ and the initial currents at commutation start angle α are $i_p = -i_{cd}$, $i_{d1} = i_{cd1}$, $i_{d2} = i_{cd2}$ and $i_d = i_{cd1} + i_{cd2}$. Commutation state ends, when i_p becomes equal to i_d .

- (c) Rectification state ($\alpha + u \leq \theta \leq \pi + \alpha$)

In the rectification state, the equivalent circuit is composed of the AC side circuit and the DC side circuit. Hence, the circuit equations are given in the following differential equations;

$$e_a = R_p i_p + X_p \frac{d i_p}{d \theta} + R_d i_{d2} + X_d \frac{d i_{d2}}{d \theta} \quad (11)$$

$$R i_{d1} + X_c \int i_{d1} d \theta = R_d i_{d2} + X_d \frac{d i_{d2}}{d \theta} \quad (12)$$

$$i_p = i_d = i_{d1} + i_{d2} \quad (13)$$

$$q = (\int i_{d1} d \theta) / \omega \quad (14)$$

$$e_a = E_m \sin \theta \quad (15)$$

By the solutions of these equations each i is as follows;

$$i_{d1} = Z_2 E_m \left\{ Z_3 \cos(\theta + \phi_2) + Z_4 \sin(\theta + \phi_1) \right\} / (Z_3^2 + Z_4^2) + \sum_{n=1}^s \omega P_n K_n \exp\{P_n(\theta - \alpha - u)\} \quad (16)$$

$$i_{d2} = E_m [X_d \sin \theta - Z_2 \{ (Z_5 Z_3 + Z_6 Z_4) \times \sin(\theta + \phi_2) + (Z_6 Z_3 - Z_5 Z_4) \times \cos(\theta + \phi_2) \} / (Z_3^2 + Z_4^2)] / Z_7 - \sum_{n=1}^3 T_n K_n \exp \{ P_n(\theta - \alpha - u) \} \quad (17)$$

$$i_p = i_d = i_{d1} + i_{d2} \quad (18)$$

where the initial values at rectification start angle $\alpha + u$ are $i_{d1} = i_{R1d1}$, $i_{d2} = i_{R1d2}$ and $q = q_R$. In these equations, $Z_1 \sim Z_7$, ϕ_2 , T_n and K_n are constants and are shown in appendix.

(d) Flowchart of calculation

In the case of mode 1, the flowchart of each current calculation using the above-mentioned equations is shown in Fig.4.

B. Analysis of mode 2

In the CR series circuit, when C is large or R is small in comparison with the CR constant values given by the equation (1), there is no commutation state. And the circuit gives rise to the state (Interruption state) in which no current flows in any diode.

Fig.5 shows the voltage and current waveforms in this mode. When the circuit in this mode is analyzed, rectification start angle β_1 and currents of each part in rectification and interruption states have to be calculated.

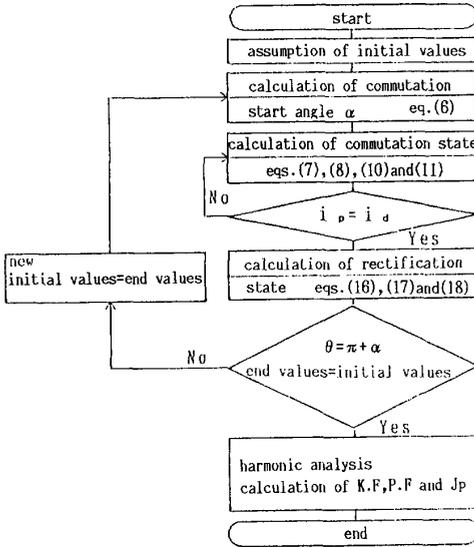


Fig.4. Flowchart of calculation(mode 1).

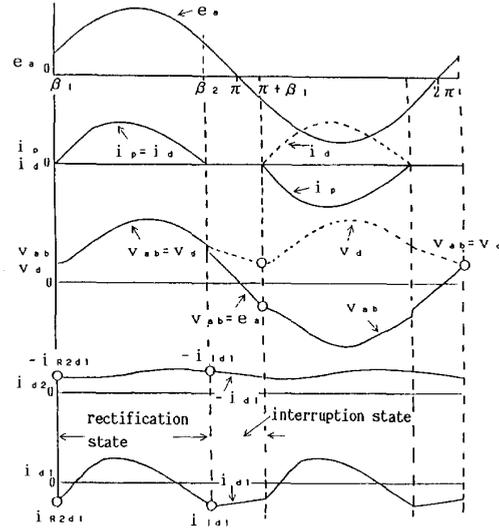


Fig.5. Voltage and current waveforms(mode 2)

(a) Rectification start angle β_1

Rectification start angle β_1 is interruption end angle at which $v_{ab} (= e_s)$ is equal to v_d .

Therefore, β_1 is shown in the following equation;

$$E_m \sin \beta_1 = R i_{R2d1} + \omega X_c q_{R2} \quad (19)$$

where current and charge at β_1 are $i_{d1} = i_{R2d1}$ and $q = q_{R2}$. Hence, from eq.(19), equation (20) is obtained;

$$\beta_1 = \sin^{-1} \{ (R i_{R2d1} + \omega X_c q_{R2}) / E_m \} \quad (20)$$

(b) Rectification state ($\beta_1 \leq \theta \leq \beta_2$)

The current in the rectification state are given by substituting β_1 for $\alpha + u$ in the eqs.(16)~(18);

$$i_{d1} = Z_2 E_m \{ Z_3 \cos(\theta + \phi_2) + Z_4 \sin(\theta + \phi_1) \} / (Z_3^2 + Z_4^2) + \sum_{n=1}^3 \omega P_n K_n \exp \{ P_n(\theta - \beta_1) \} \quad (21)$$

$$i_{d2} = E_m [X_d \sin \theta - Z_2 \{ (Z_5 Z_3 + Z_6 Z_4) \times \sin(\theta + \phi_2) + (Z_6 Z_3 - Z_5 Z_4) \times \cos(\theta + \phi_2) \} / (Z_3^2 + Z_4^2)] / Z_7 - \sum_{n=1}^3 T_n K_n \exp \{ P_n(\theta - \beta_1) \} \quad (22)$$

$$i_p = i_d = i_{d1} + i_{d2} \quad (23)$$

where the initial values at rectification start angle β_1 are $i_{d1} = i_{R2d2}$, $i_{d2} = i_{R2d1}$ and $q = q_{R2}$. When i_{d2} is equal to capacitor discharge current i_{d1} , rectification state ends.

The constants in the eqs.(21)~(23) are equal to the values(appendix) which are obtained by substituting, respectively, initial values $\beta_1, i_{R2d1}, -i_{R2d2}$ and q_{R2} for $\alpha + u, i_{R1d1}, i_{R1d2}$ and q_{R1} .

(c) Interruption state ($\beta_2 \leq \theta \leq \pi + \beta_1$)

In the interruption state, the charged energy in capacitor is supplied to the load and the circuit is composed of the closed circuit on the DC side.

Hence, the circuit equations are given in the following differential equations;

$$R i_{d1} + X_c \int i_{d1} d\theta = R_d i_{d2} + X_d d i_{d2} / d\theta \quad (24)$$

$$i_{d1} = -i_{d2} \quad (25)$$

$$q = (\int i_{d1} d\theta) / \omega. \quad (26)$$

By the solutions of the equations (2)~(5) each i and v are shown in the following equations;

$$i_{d1} = -i_{d2} = \exp\{-\delta(\theta - \beta_2)\} [i_{1d1} \times \cos \gamma(\theta - \beta_2) - \{\omega \gamma q_1 + \delta(i_{1d1} + \omega \delta q_1) / \gamma\} \sin \gamma(\theta - \beta_2)] \quad (27)$$

$$i_p = i_d = i_{d1} + i_{d2} \quad (28)$$

$$v_d = \exp\{-\delta(\pi + \beta_1 - \beta_2)\} [(R i_{1d1} + \omega X_c q_1) \cos \gamma(\pi + \beta_1 - \beta_2) - \{R \omega \gamma q_1 + (R \delta - X_c)(i_{1d1} + \omega \delta q_1) / \gamma\} \times \sin \gamma(\pi + \beta_1 - \beta_2)] \quad (29)$$

where the condition of the circuit constants is in the vibratory case. Then,

$$\delta = (R + R_d) / (2X_d) \\ \gamma = \sqrt{4X_c X_d - (R + R_d)^2} / 2X_d.$$

And, initial values at interruption start angle β_2 are $i_{d1} = -i_{d2} = i_{1d1}$ and $q = q_1$. When $v_{as}(=e_a)$ becomes equal to v_d , interruption state ends.

(d) Flowchart of calculation

In the case of mode 2, flowchart of each current calculation using the equations given above are shown in Fig.6.

IV. ANALYSIS RESULTS AND CONSIDERATION

By using the analysis way shown in the former chapter, the analysis results considered the condition of electric railway are shown in the following.

A. Circuit condition and waveforms of voltage and current

In the electric railway, the constant values of the popular DC motor MT-52 in the rated load condition are $R=0.394\Omega$, $X=1.496\Omega$ and $E=675.8V$ (equivalent resistance $R_e=1.185\Omega$). Including the impedance of smoothing reactor, their values[10] are $R_t=0.415\Omega$ and $X_d=2.28\Omega$ as the values corresponding to the circuit configuration.

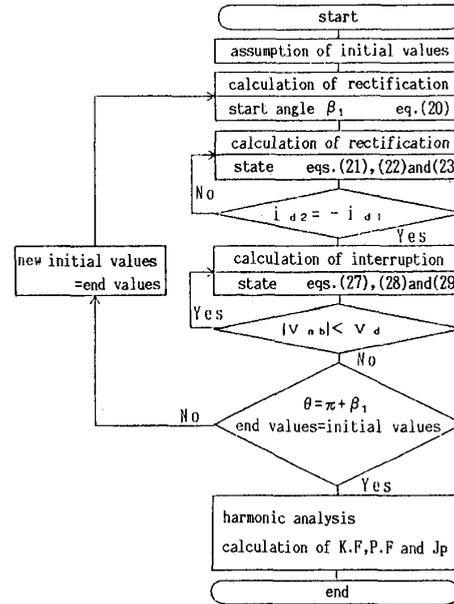


Fig.6. Flowchart of calculation(mode 2).

For example, in the ED75 system[11][12], their constants variable limits owing to change of the load current value are $R_t=0.385\sim 0.555\Omega$ and $X_d=2.08\sim 5.58\Omega$. Also, impedance ratios among the constants in the electric railway circuit are $K_d=X_d/R_t=5\sim 15$, $K_L=X_p/X_d=0.05\sim 0.3$ and $K_R=R_p/R_t=0.1\sim 0.3$, and, the turn ratio n [12] of the main transformer is $n=16.0$, etc..

The rated capacity of the main transformer used in the experiment is 200VA. Rated primary voltage is 100V($f=60Hz$) and rated secondary voltage is 15V. Turn ratio $n=N_1/N_2 \approx 6.67$. Secondary leakage reactance is 0.0314Ω . Each circuit constant value used in the experiments is about six times larger than practical values owing to the restriction of the experiment system. Then, the impedances on the AC side converted into secondary side are $R_p=0.74\Omega$ and $L_p=3.6mH$. Assuming that the constant values of the motor in the rated condition are maximum load constants, values of R_t , R_e and L_d are 2.5Ω , 7.0Ω and $36mH$. Also, because the values of impedance ratio K_d , K_L and K_R are 5.4, 0.1 and 0.3, they are within the range of the practice example.

Figs.7(a),(b) show examples of the voltage and current waveforms in the experiments. Fig.7(a) shows waveforms in the case of the CR series circuit non-insertion. Fig.7(b) shows waveforms in the case of the CR series circuit insertion($C=400\mu F, R=9.5\Omega$) and their values satisfy nearly the constant resistance condition. Each symbol corresponds to Fig.1. In the waveforms of Fig.7(a), i_p shows change like a square wave in the neighborhood of phase angle zero and

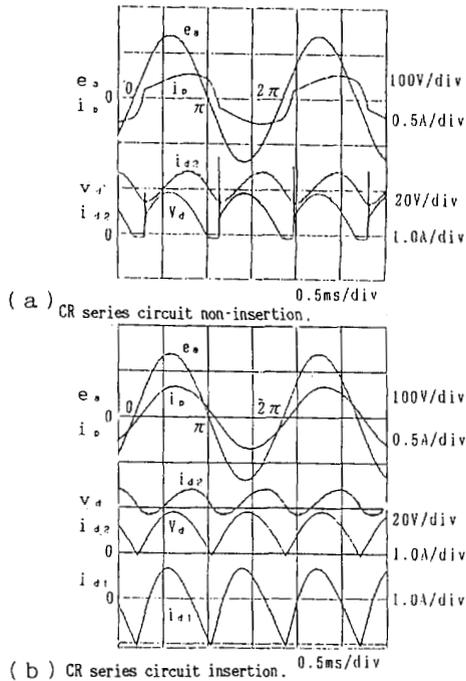


Fig.7. Experimental waveforms of voltage and current.

pai. Therefore, i_p contains a large quantity of high harmonics. Also, the rectifier circuit gets into the state that instantaneous value of v_d is zero (commutation state). And, the ripple of i_{d2} is low due to the load reactance. In the waveforms of Fig.7(b), accompanied by insertion of the CR circuit, i_p approaches a sine waveform. i_{d2} shows change very little by inserting the CR circuit. i_{d1} reiterates charge and discharge in the two times frequency of the power source in accordance with magnitude relation between v_d and capacitor voltage.

From the above-mentioned, in the constant resistance condition, it was made sure that i_p approaches a sine waveform and that it contains high harmonics very little.

B. Characteristics for constants change of the CR series circuit

In this paragraph, reduction effect of the high harmonics for constants change of the CR series circuit is investigated. Also, it shows considerations for selection of the circuit constant values. These investigations are given in the condition of the load power 21.4W constant.

(a) Efficacy for third harmonic current, Klirr Factor and Total Power Factor.

The definitions[13] of Klirr Factor and Total Power Factor are shown in the following equations;

$$\text{Klirr Factor } K. F = I_h / I_o \quad (30)$$

$$\text{Total Power Factor } P. F = I_1 / I_o \cos \phi_1 \quad (31)$$

where

$$I_o = \sqrt{\sum_{k=1}^{\infty} I_n^2}, \quad I_h = \sqrt{\sum_{k=1}^{\infty} I_m^2}$$

$$n = 2k - 1, \quad m = 2k + 1$$

ϕ_1 = phase difference between the fundamental harmonic voltage and current.

I_1 = effective value of the fundamental harmonic current.

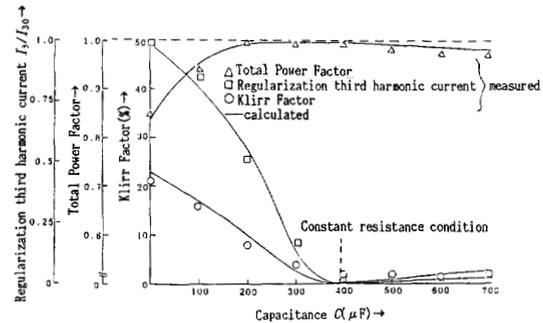


Fig.8. Capacitance vs. third harmonic current, Power Factor and Klirr Factor.

Fig.8 shows the characteristics of third harmonic current, Klirr Factor and Total Power Factor for variation of the CR circuit constants on the condition that the value of impedance on the AC side and the load constant are fixed. Because investigation of this method is aimed at reduction of equivalent disturbing current J_p , the value of the resistance R for C except for the constant resistance condition is selected in the condition which the value of J_p is the lowest.

The third harmonic current is regularized by the value of third harmonic current I_{30} in $C=0$. As their results show, third harmonic current and Klirr Factor are zeros in the constant resistance condition and even if C is small, the effect is enough.

In Total Power Factor, even if value of C is very small, the effect is great. The calculation results agree with the experimental results in Fig.8.

(b) Effect for the equivalent disturbing current J_p and loss.

Considering the induction obstacle of the communication lines, it is customary that the disturbance degree is evaluated by the equivalent disturbing current. According to CCITT[14], the definition is revealed in the equation, as follows;

$$J_p = \sqrt{\sum_n (S_n I_n)^2} \quad (32)$$

where

I_n : effective value of the nth harmonic
 S_n : noise evaluation coefficient.

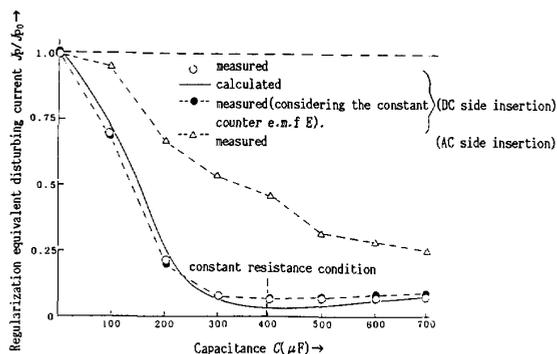


Fig.9. Capacitance vs. J_p/J_{p_0}

Fig.9 shows the characteristics of J_p , compared this method with the case of inserting the CR circuit into the AC side. The values of the CR circuit constant in Fig.9 and Fig.8 are the same. Vertical axis is regularized by the value (J_{p_0}) of J_p in $C=0$.

Experimental results considered the constant e.m.f E are shown in Fig.9. As the result shows, value of C on the DC side is efficacious in the value given by the constant resistance condition or more than it. The calculation results agree with the experimental results in Fig.9. J_p of AC side insertion is about ten times as large as J_p of the DC side insertion in the constant resistance condition.

Therefore, the reduction effect of the CR circuit on the DC side is good.

Sign● is much the same result as sign○ substituted the resistance for the constant counter e.m.f E. Hence, it was made sure that substituting the resistance is pertinent.

According to the reports of UIC the fifth steering committee, electrification sectional meeting and WG-5-A-22, the reduction effect of J_p in former method inserted the AC tuned filter is about 1/3.7 in the examination results by the car of Sweden National Railways. Also, according to the measurement examples used the 951 type examination car of JR, it is reported that J_p becomes within the range of 1/1.04~1/1.78.

The reduction effect of this method is very good as contrasted with these results.

Next, Fig.10 shows increase rate $((I_{p,CR} - I_p)/I_p \times 100)$ of AC current and power loss $(P_{CR}/P_a \times 100)$ of the CR series circuit for variation of the capacitance as contrasted with the AC side insertion

where

- I_p : effective value of the current on the AC side in the case of the CR circuit non-insertion
- $I_{p,CR}$: effective value of the current on the AC side in the case of the CR circuit insertion
- P_{CR} : effective power of the CR circuit
- P_a : total effective power.

The conditions of Fig.10 and Fig.9 are the same. As shown in Fig.10, in the constant resistance condition of the DC side insertion, increase rate of the AC current becomes

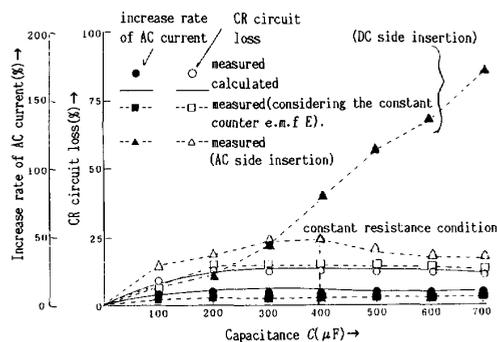


Fig.10. Capacitance vs. increase rate of AC current and power loss of CR series circuit.

maximum value (about 13%). Likewise, in the AC side insertion, it becomes about 80%. Also, in the rectifier circuit inserted the CR circuit into the DC side, no matter how much the C increases, I_p does not increase. But, in the rectifier circuit inserted the CR circuit into the AC side, the more C increases, the more i_p increases, because the fundamental harmonic current flows into the CR circuit on the AC side. In the AC side insertion, maximum value of the CR circuit loss is about 24%, and in the DC side insertion, its maximum value is about 13%.

It is evident from the above-mentioned that connecting the CR circuit with the DC side is a profitable method.

(c) Effect for J_p of the inductive reactance on the AC side.

In order to know the effect for J_p of the inductive reactance on the AC side, calculation results of the J_p/J_{p_0} for the CR circuit time constant with the parameter of the inductive reactance on the AC side are shown in Fig.11.

It can be seen from the results that in the constant resistance condition ($C=398.89 \mu F$, $R=9.5 \Omega$, Time constant is $3789 \mu s$), striking reduction effect can be got and the

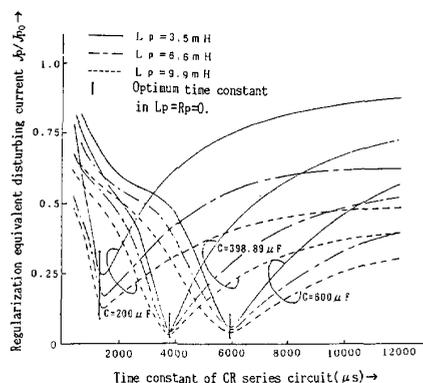


Fig.11. Time constant of CR series circuit vs. J_p/J_{p_0} .

value is 5% as contrasted with J_p of the CR circuit non-insertion. Further, J_p shows minimum point without reference to magnitude of the inductive reactance on the AC side. Also, in the case of ($C=200\mu F$, time constant $1300\mu s$) and ($C=600\mu F$, time constant $6000\mu s$), their characteristics are similar to the above-mentioned one. When the more different the time constant is from optimum point, the greater the effect for J_p of the inductive reactance on the AC side is. And, the smaller L_p is, the higher the relative value of J_p is.

In the diagram, in the absence of the impedance on the AC side, $\text{sign}|\tau$ is the time constant in the minimum value of J_p . In the presence of the impedance on the AC side, this time constant is approximately same value in comparison with it. Therefore, when the load constants are given, the best CR circuit constants can be determined without reference to the impedance on the AC side.

C. Effect for J_p of the load variation (considering the inductive reactance variation on the AC side)

In this paragraph, assuming a tap control car, the characteristics of J_p for the load variation are investigated on the assumption that load current is constant control and that turn ratio of the main transformer is $n=16.0$ in the maximum load condition. In the investigation of this paragraph, the load variation means variation of the constant counter e.m.f E accompanied by a speed control.

In this investigation, because the constant counter e.m.f E is estimated as $R_e=7.0\Omega$ in the maximum load condition, Fig.12 shows the characteristics of J_p calculated by changing the value of R_e from 0Ω to 7.0Ω . However, the load current i_{d2} is $1.5A$ constant. J_p is obtained from values converted into primary side by computing the turn ratio for each secondary voltage. In addition, constant values of the CR circuit are selected under the condition that J_p becomes minimum value in the maximum load condition. As the results show, it can be seen that J_p is greatly suppressed for increase of the load average power in each capacitor. Also, in the case of the CR circuit insertion, when the inductivity reactance on the AC side increases,

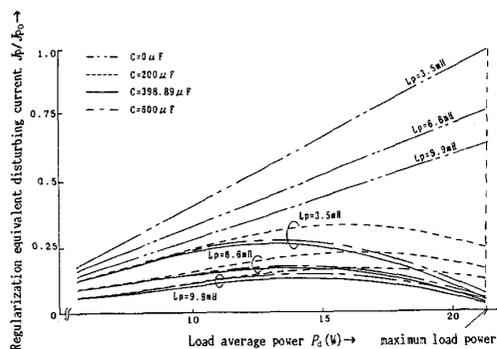


Fig.12. load average power vs. J_p/J_{p0} .

the value of J_p becomes relatively low like in the case of the CR circuit non-insertion.

From the above-mentioned, it is confirmed that if best value of the CR circuit constants is selected in the maximum load condition, the circuit can always maintain low value of J_p .

V. CONCLUSION

The proposed method in this paper can make the high harmonic currents on the AC side reduce by getting the correct harmonic distribution on the DC side by connecting the CR circuit with the DC side.

The investigation results of a tap control car applied this method can be summed up as follows.

- 1) The best value of the CR circuit constants is given in the constant resistance condition and even if the value of C is a little different from the condition, the effect is great. Further, the best value of resistance R for the various C may be selected without reference to the impedance on the AC side in the electric railway circuit condition.
- 2) In the constant resistance condition, the value of the equivalent disturbing current J_p is 5% as contrasted with the CR circuit non-insertion.
- 3) The effects for Klirr Factor and third harmonic current are great too. And it can be said that much hope is found in the reducing third harmonic current at the inside of the car.
- 4) Increase in size of capacitor kVA accompanied by the fundamental harmonic current inflow is small and the reduction effect of high harmonic currents is great too. Further, Total Power Factor also can be improved.
- 5) J_p is low within the wide range of the load variation and even maximum value is about 25%. Therefore, by using this method, it becomes possible to narrow a generation area of the induction obstacle.

From these results, it is confirmed that this method has much effect on the reduction of high harmonic currents and improvement of Power Factor.

At the present time, the devices used the rectifier circuits are on the increase year by year. Hence, it may appear that the reduction countermeasure of high harmonic currents generated from the devices will be investigated in future.

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$$K_3 = \frac{[q_{R1}(Z_3^2 + Z_4^2) - Z_2 E_m \{Z_3 \sin(\alpha + u + \phi_2) - Z_4 \cos(\alpha + u + \phi_2)\} / \omega] / (Z_3^2 + Z_4^2) + \{(T_2 - T_1) \xi - (P_1 - P_2) \lambda\} / \Delta}{\Delta = (T_3 - T_2)(P_1 - P_3) - (T_3 - T_1)(P_2 - P_3)}$$

P_1, P_2 and P_3 are root of the characteristic equation and their values are shown in the following;

$$P_1 = -x - y - z$$

$$P_2 = -\omega x - \omega^2 y - z$$

$$P_3 = -\omega^2 x - \omega y - z$$

where

$$a = \{R_d R_p + X_c(X_p + X_d) + R(R_p + R_d)\} / X_p X_d$$

$$b = X_c(R_p + R_d) / X_p X_d$$

$$\omega = (-1 \pm j\sqrt{3}) / 2$$

$$x = \sqrt[3]{b/2 + \sqrt{b^2/4 + a^3/27}}$$

$$y = \sqrt[3]{b/2 - \sqrt{b^2/4 + a^3/27}}$$

$$z = (R_d + R) / (3X_d) + (R_p + R) / (3X_p)$$

APPENDIX

Each constant of the eqs.(16)~(18) is shown in the following equations;

$$Z_2 = \sqrt{R_d^2 + X_d^2}, \phi_2 = \tan^{-1}(X_d/R_d)$$

$$Z_3 = X_c(R_p + R_d) - X_p R_d - Z_6$$

$$Z_4 = R(R_p + R_d) + R_d R_p + Z_5$$

$$Z_5 = X_c(X_p + X_d) - X_d X_p$$

$$Z_6 = X_d R_p + R(X_p + X_d)$$

$$Z_7 = X_d R_p - X_p R_d$$

$$T_n (n=1, 2, 3) = \omega (P_n^2 X_d X_p + P_n Z_6 + X_p X_d + Z_5) / Z_7$$

$$\xi = Z_2 [(i_{R1d1} - \omega P_3 q_{R1})(Z_3^2 + Z_4^2) / Z_2 - E_m \{(Z_4 - P_3 Z_3) \sin(\alpha + u + \phi_2) + (Z_3 + P_3 Z_4) \cos(\alpha + u + \phi_2)\}] / \{\omega(Z_3^2 + Z_4^2)\}$$

$$\lambda = \frac{[i_{R1d2} + T_3 q_{R1} - X_d E_m \sin(\alpha + u) / Z_7] \times (Z_3^2 + Z_4^2) + Z_2 E_m \{Z_3(Z_5 - T_3 Z_7 / \omega) + Z_6 Z_4\} \sin(\alpha + u + \phi_2) + \{Z_6 Z_3 - Z_4(Z_5 + T_3 Z_7 / \omega)\} \cos(\alpha + u + \phi_2)}{Z_7} / (Z_3^2 + Z_4^2)$$

$$K_1 = \{(T_3 - T_2) \xi - (P_2 - P_3) \lambda\} / \Delta$$

$$K_2 = \{(T_1 - T_3) \xi - (P_3 - P_1) \lambda\} / \Delta$$