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Transient Performance of Electrical System in a Military Vehicle

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ABSTRACT

Electrical system in a military vehicle is a low voltage (28 V dc) system which is an unsymmetrical and nonlinear system made up of silicon-rectifying generator and a battery in parallel. Studies have been carried out using numerical method to calculate its transient performance. State variable and coordinate transformation have been adopted to express the functional modes and its transfer law of the silicon-rectifying generator; the battery is expressed as a simplified equivalent circuit according to its characteristics during transient process: Consequently, the general mathematical model of electrical system in a military vehicle is presented. Examples of electrical systems in some military vehicles have been taken to carry out the calculation of transient performance and the findings have been compared with the test results of an actual vehicle to show that the numerical method designed works.

Keywords: Military vehicle, electrical system, transient performance, numerical method, silicon-rectifying generator

1. INTRODUCTION

In recent years, electrical system in a military vehicle is a low voltage (28 V dc) system, in which the generator, called silicon-rectifying generator, is an ac generator with silicon rectifier, and a battery as auxiliary power is connected with the generator in parallel, so the electrical system in a military vehicle is an unsymmetrical and nonlinear system. The electricity requirement of the electrical system in a military vehicle is nearly equivalent to the capability of the generator, and its functional modes change frequently so the voltage of the electrical system in a military vehicle appears with radical changes. For example, for a 28 V dc electrical system in a military vehicle, the initial engagement surge of the engine in the system may be low to 6 V when it is started, and its spike may be high to 250 V when the motor load is cut suddenly.

In practice, the transient performance of the electrical system in a military vehicle is difficult to compute using analytical method. So, this study is based on calculating it using a computer to provide the rationale for optimisation design and correct application in terms of composition and application characteristic of the electrical system in a military vehicle.

2.1 Functional Mode of Silicon-rectifying Generator

The functional mode of a bridge rectifier have two modes of commutation and conduction as shown in Fig. 1.

The conduction between the phases A and B is shown in Fig. 1(a). The conduction condition between phase A and phase B is $u_a > u_b$ and the

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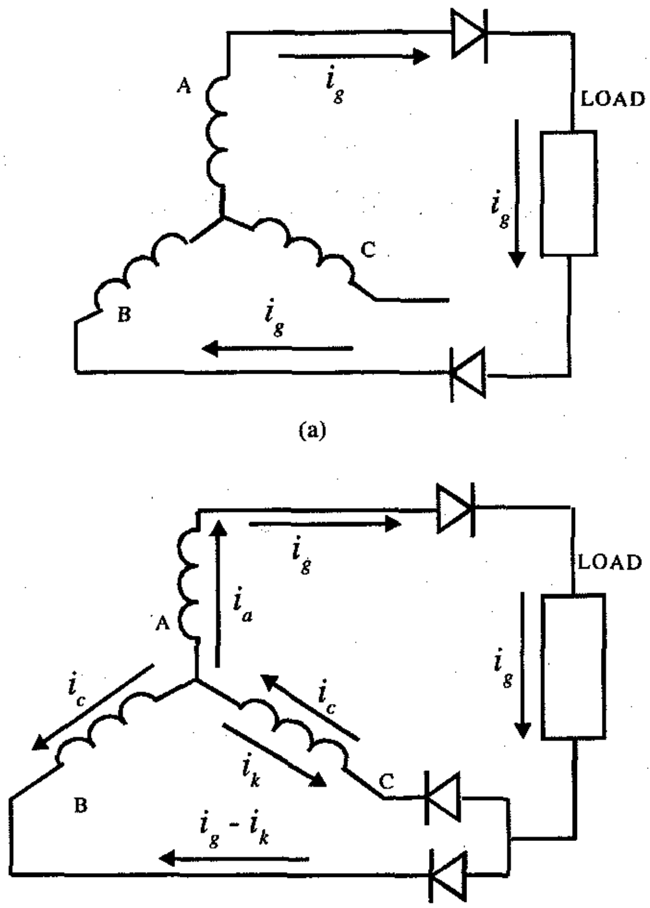

(a)

(b)

Figure 1. Functional mode of bridge rectifier

output voltage of bridge rectifier, u_g is:

$$u_g = u_a - u_b \tag{1}$$

The relation of current is:

$$i_c = 0, \quad i_g = i_a = - i_b \tag{2}$$

The running conditions of six conduction modes are listed in Table 1.

In three-phase bridge connection, the ideal conduction time interval corresponds with $(360^\circ \div 6) = 60^\circ$ when the commutation process doesn't exist; when the commutation process exists, the conduction time interval corresponds with $(60^\circ - \mu)$. The conduction time interval is:

$$t_T = (60^\circ - \mu)/\omega \tag{3}$$

where μ is the commutation overlap angle and ω is the electrical angular velocity in radian/second.

Figure 1(b) is the commutation mode from conduction between phase A and B to phase A and C. At the beginning of commutation, $u_b = u_c$. The time interval during commutation corresponds with commutation overlap angle, μ.

The commutation current, i_k, during commutation is:

$$i_k \approx \frac{u_g}{2x_\sigma}(1 - \cos \omega t) \tag{4}$$

where x_σ is the phase leakage reactance of the generator.

Table 1. Running conditions of conduction modes

Modes	Abridge notation	Running conditions	Voltage relation	Current relation
1	$A'B^-$	$u_a > u_c > u_b$, $i_c = 0$	$u_g = u_a - u_b$	$i_a = i_g$, $i_b = -i_g$
2	$A'C^-$	$u_a > u_b > u_c$, $i_b = 0$	$u_g = u_a - u_c$	$i_a = i_g$, $i_c = -i_g$
3	$B'C^-$	$u_b > u_a > u_c$, $i_a = 0$	$u_g = u_b - u_c$	$i_b = i_g$, $i_c = -i_g$
4	$B'A^-$	$u_b > u_c > u_a$, $i_c = 0$	$u_g = u_b - u_a$	$i_b = i_g$, $i_a = -i_g$
5	$C'A^-$	$u_c > u_b > u_a$, $i_b = 0$	$u_g = u_c - u_a$	$i_c = i_g$, $i_a = -i_g$
6	$C'B^-$	$u_c > u_a > u_b$, $i_a = 0$	$u_g = u_c - u_b$	$i_c = i_g$, $i_b = -i_g$

Let the current put out to load be i_g, the relations between currents during commutation are:

$$i_a = i_g,\ i_b = -i_g + i_k,\ i_c = -i_k \tag{5}$$

At the instant of commutation, $i_k = 0$; after commutation overlap angle, commutation process is over.

$$i_k = i_g = -i_c \approx \frac{u_g}{2x_\sigma}(1-\cos\mu)$$

so commutation overlap angle is also expressed as

$$\mu \approx \cos^{-1}\left(1-\frac{2x_\sigma i_g}{u_g}\right) \tag{6}$$

The commutation time interval, t_H, is:

$$t_H = \mu/\omega \tag{7}$$

The output voltage of rectifier during commutation is

$$u_g = (u_a+u_b)/2-u_c \tag{8}$$

During conduction and commutation, the relationship between the voltages and the currents are shown in Figs 2(a) and 2(b).

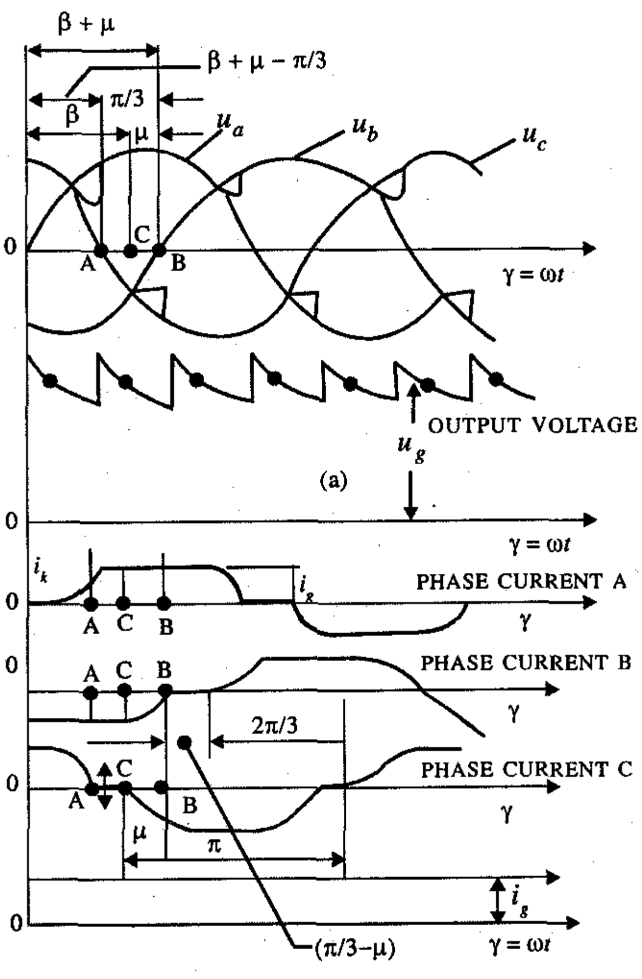

Figure 2. Relationship between (a) voltages and (b) currents.

The running condition modes of three-phase bridge rectifier are shown in Table 2.

Table 2. Running conditions of commutation modes

Nodes	Abridge notation	Running conditions	Voltage relation	Current relation
1	$A^+B^-C^-$	$u_a > u_c = u_b$	$u_g > u_c - (u_b + u_c)/2$	$i_a = i_g,\ i_b = i_g + i_k,\ i_c = -i_k$
2	$A^+B^+C^-$	$u_a = u_b > u_c$	$u_g > u_c - (u_b + u_c)/2 - u_c$	$i_c = -i_c,\ i_a = i_g - i_k,\ i_b = -i_k$
3	$B^+C^-A^-$	$u_b > u_c = u_a$	$u_g = u_b - (u_c + u_a)/2$	$i_b = i_g,\ i_c = -i_g - i_k,\ i_a = -i_k$
4	$B^+C^+A^-$	$u_b = u_c > u_a$	$u_g = (u_b + u_c)/2 - u_a$	$i_a = -i_g,\ i_a = -i_g + i_k,\ i_b = -i_k$
5	$C^+A^-B^-$	$u_c > u_a = u_b$	$u_g = u_c - (u_a + u_b)/2$	$i_c = -i_g,\ i_a = -i_g + i_k,\ i_b = -i_k$
6	$C^+A^+B^-$	$u_c = u_a > u_b$	$u_g = (u_c + u_a)/2 - u_a$	$i_b = -i_g,\ i_c = i_g - i_k,\ i_a = -i_k$

$$\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} A^+ \\ B^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} & A^+ & \\ B^- & & C^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} A^+ \\ C^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} A^+ & & B^+ \\ & C^- & \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} B^+ \\ C^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} & B^+ & \\ C^- & & A^- \end{bmatrix}$$

$$\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} B^+ \\ A^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} B^+ & & C^+ \\ & A^- & \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} C^+ \\ A^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} & C^+ & \\ A^- & & B^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} C^+ \\ B^- \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} C^+ & & A^+ \\ & B^- & \end{bmatrix}\begin{array}{c}\rightarrow\\ \Leftarrow\end{array}\begin{bmatrix} A^+ \\ B^- \end{bmatrix}$$

Figure 3. Transfer law of modes

3. TRANSFORMATION OF FUNCTIONAL MODES

The three-phase ac voltages across rectifier alternate, and the conduction and commutation modes of rectifier too alternate, which result in six conduction and commutation modes. During running, the rectifier gets transfered from one mode to another mode. The transfer law of modes is shown in Fig. 3.

The arrow "$\rightarrow$" in Fig. 3 denotes ideal mode transfer. When three-phase voltage is sine symmetrical and six diodes conduct and cutoff according to normal law, the mode transfer is ideal. If three-phase voltage is unsymmetrical sequence or negative-phase sequence, the rectifier does not transfer according to ideal modes. So, an assistant transfer route is needed. "$\Rightarrow$" Figure 3 denotes assistant transfer route of a non-ideal mode.

One side of the rectifier is input and a three-phase ac is applied; the other of it is output and side dc is put out. Twelve relations between input and output are got according to 12 functional modes used for transformation between ac and dc of the rectifier.

State variable and coordinate transformation methods are adopted when the relations between input and output are analysed. The transformation between d,q,o coordinate system and a,b,c coordinate system is:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \\ u_f \end{bmatrix} = \begin{bmatrix} p & -\omega & 0 & 0 \\ \omega & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_0 \\ \psi_q \end{bmatrix} + \begin{bmatrix} -r_a & 0 & 0 & 0 \\ 0 & -r_a & 0 & 0 \\ 0 & 0 & -r_a & 0 \\ 0 & 0 & 0 & -r_a \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_o \\ i_f \end{bmatrix}$$

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_0 \\ \psi_f \end{bmatrix} = \begin{bmatrix} -x_d & 0 & 0 & x_{ad} \\ 0 & -x_q & 0 & 0 \\ 0 & 0 & -x_o & 0 \\ -x_{ad} & 0 & 0 & x_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \\ i_{qf} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} u_a & i_a \\ u_b & i_b \\ u_c & i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta-120^\circ\right) & -\sin\left(\theta-120^\circ\right) \\ \cos\left(\theta+120^\circ\right) & -\sin\left(\theta+120^\circ\right) \end{bmatrix} \begin{bmatrix} u_d & i_d \\ u_q & i_q \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} u_d & i_d \\ u_q & i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta-120^\circ\right) & \cos\left(\theta+120^\circ\right) \\ -\sin\theta & -\sin\left(\theta-120^\circ\right) & -\sin\left(\theta+120^\circ\right) \end{bmatrix} \begin{bmatrix} u_a & i_a \\ u_b & i_b \\ u_c & i_c \end{bmatrix} \tag{12}$$

Let the output dc of the rectifier be i_g and the expressions can be achieved after transformation as

During conduction

$$\begin{aligned} i_d &= SS_1 \sin AA_1 * i_g \\ i_q &= -SS_1 \cos AA_1 * i_g \end{aligned} \tag{13}$$

where SS_1 and AA_1 are related to the functional mode of conduction shown in Table 3.

During commutation

$$i_d = SS_2 \ \sin \ AA_2^* \ i_g - SS_3 \ \sin \ AA_3^* \ i_k$$

$$i_q = -SS_2 \ \cos \ AA_2^* \ i_g + SS_3 \ \cos \ AA_3^* \ i_k$$

Table 3. Relationship of SS_1 and AA_1 with the functional mode of conduction

Modes	SS_1	AA_1
1	$-2/\sqrt{3}$	$\theta - 60°$
2	$2/\sqrt{3}$	$\theta + 60°$
3	$2/\sqrt{3}$	θ
4	$2/\sqrt{3}$	$\theta - 60°$
5	$-2/\sqrt{3}$	$\theta + 60°$

where SS_2, SS_3, AA_2 and AA_3 are related to the functional mode of commutation which is shown in Table 4.

4. FIELD CIRCUIT OF GENERATOR IN A VEHICLE

Generally, the generator in a vehicle has field regulator. To simplify the problem, the transient process of field regulator is ignored, that is to say the increment of the voltage across the generator acts on the field circuit of the generator and the exciting change of the generator results in the electromagnetic force change of generator. So, the equation of field circuit needs to be added into the state equation of the generator.

$$\begin{aligned} u_f &= L_f \frac{di_f}{dt} + R_f i_f \\ u_f &= K_s\left(u_{gN} - u_g\right) + u_{fN} \end{aligned} \tag{15}$$

Table 4. Relationship of SS_2, SS_3, AA_2 and AA_3 with the functional mode of commutation

Modes	SS_2	SS_3	AA_2	AA_3
1	$2/\sqrt{3}$	$-2/\sqrt{3}$	$\theta - 60°$	$\theta + 60°$
2	$-2/\sqrt{3}$	$2/\sqrt{3}$	$\theta - 60°$	$\theta + 60°$
3	$2/\sqrt{3}$	$-2/\sqrt{3}$	$\theta + 60°$	θ
4	$-2/\sqrt{3}$	$2/\sqrt{3}$	$\theta + 60°$	θ
5	$2/\sqrt{3}$	$-2/\sqrt{3}$	θ	$\theta - 60°$
6	$-2/\sqrt{3}$	$2/\sqrt{3}$	θ	$\theta - 60°$

where u_{gN}, u_{fN} indicate the given voltage across the generator and the exciting circuit and K_s is the scale coefficient of the regulator

5. EQUIVALENT CIRCUIT OF THE BATTERY

The voltage across the battery is looked as the sum of the following three components:

$$u = e_b + e_p + iR_0 \tag{16}$$

where e_b is the equilibrium electromagnetic force, e_p is the polarisation electromagnetic force, i is the battery current, and R_o is the internal resistance.

The relationship beween equilibrium electromagnetic force and the current flowing in the battery is in the range of the normal running battery as

$$e_b = e_0 + \alpha_b \int_0^t i dt \tag{17}$$

where t is the working time, e_0 is the equilibrium electromagnetic force when $t = 0$, and a_b is the variation coefficient of equilibrium electromagnetic force.

$$e_p = 0.052\sqrt{\frac{D}{\pi}} \int_0^t \frac{\Psi(\tau)}{\sqrt{t-\tau}} \mathrm{dt} \tag{18}$$

where D is the diffusion coefficient of vitriol and $\Psi(t)$ is the lying o*n* the rules of current and interface area change with time.

When the battery works on the inner part and the temperature of electrolyte keep invariability:

$$\Psi(\tau) = -\frac{i}{ZFSD} \tag{19}$$

where Z is the valence of diffusion ion, F is the Faraday constant , and S is the area of the interface between electrolyte and electrode.

Applying Eqns (17) and (18) to Eqn (16) results in

$$u = e_o + \alpha_b \int_0^t i dt + \frac{\beta}{2} \int_0^t \frac{i(\tau)}{\sqrt{t-\tau}} d\tau + i(t) R_0 \qquad (20)$$

where

$$\beta = \frac{0.104}{ZFS\sqrt{\pi D}}$$

The constant term is not calculated and only the alternating component is taken into account, namely:

$$u-(t) = \alpha_b \int_0^t i dt + \frac{\beta}{2} \int_0^t \frac{i(\tau)}{\sqrt{t-\tau}} d\tau + i(t) R_0 \qquad (21)$$

The Laplace transform is adopted to achieve when initial condition is zero:

$$U(p) = \left(\frac{\alpha_b}{p} + \frac{\beta\sqrt{\pi}}{2\sqrt{p}} + R_0 \right) I(p) \qquad (22)$$

The transfer function is:

$$W(p) = \left(\frac{\alpha_b}{p} + \frac{\beta\sqrt{\pi}}{2\sqrt{p}} + R_0 \right) \qquad (23)$$

The Eqn (23) can be looked as characteristic impedance in the form of operator and the impedance of the battery can be achieved replacing p by $j\omega$:

$$Z(j\omega) = \frac{\alpha_b}{j\omega} + \frac{\beta\sqrt{\pi}}{2\sqrt{j\omega}} + R_0 \qquad (24)$$

where the first term can be taken as the capacitive reactance of capacity (C_b).

The second term can be taken as RC cable for the impedance of even long line with distributing capacity when inductive reactance is ignored and relations can be found as follows:

$$\frac{\beta\sqrt{\pi}}{2} = \sqrt{\frac{r}{c}} \qquad (25)$$

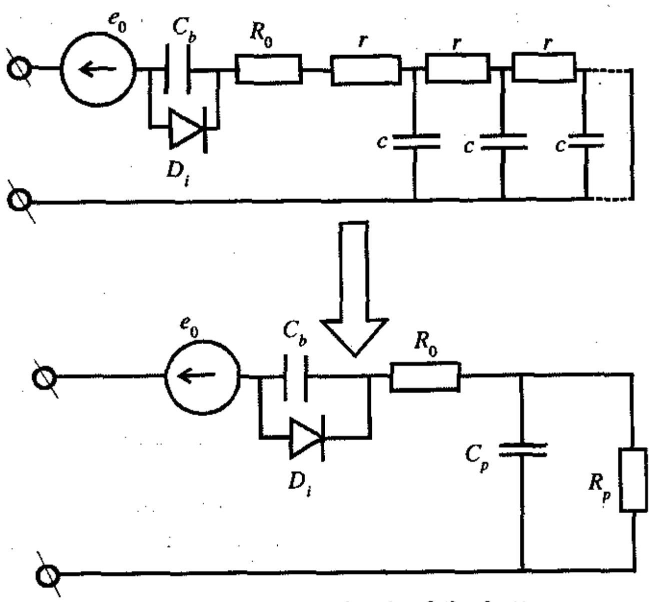

Figure 4. Equivalent circuit of the battery

Consequently the equivalent circuit of battery is shown in Fig. 4.

The function of diode, D_i, is to limit equilibrium electromagnetic force to e_0. C_b is 2.5 x 10^2 F and C_p is 18 F in the type-A 140 Ah starting battery, thus C_b can be taken as short circuit during transient

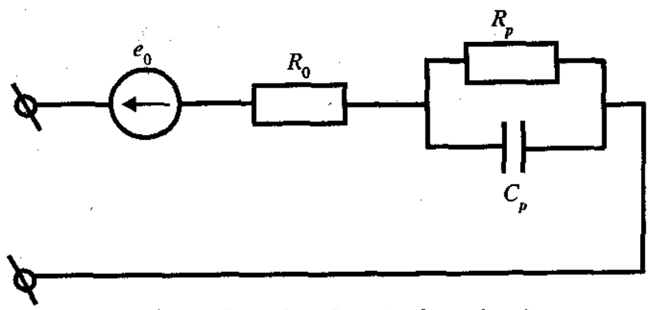

Figure 5. Reduced equivalent circuit

process. The reduced equivalent circuit can be shown in Fig. 5.

6. EQUIVALENT CIRCUIT & EQUATION OF ELECTRICAL SYSTEM

The schematic diagram of equivalent circuit of electrical system in a military vehicle is shown in Fig. 6.

The requirement of electrical system in military vehicle includes resistance load, inductance-resistance

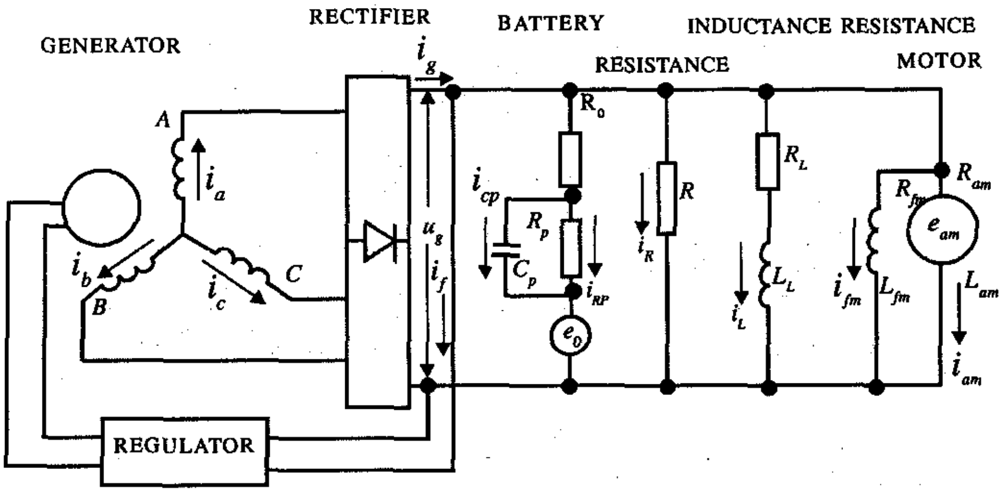

Figure 6. Schematic diagram of equivalent circuit of electrical system in military vehicle

load, and motor load. A shunt motor can be representative of all kinds of motor loads.

The following equations can be written according to Fig 6:

$$u_f = L_f \frac{di_f}{dt} + R_f i_f$$
$$u_f = K_s\left(u_{gN} - u_g\right) + u_{fN} \tag{26}$$

$$u_g = R_0 R_p C_p \frac{di_{RP}}{dt} - \left(R_0 + R_P\right) i_{RP} + e_0$$
$$i_{cp} = C_P R_P \frac{di_{RP}}{dt} \tag{27}$$

$$u_g = i_R R \tag{28}$$

$$u_g = i_L R_L + L_L \frac{di_L}{dt} \tag{29}$$

$$u_g = e_{am} + R_{am} i_{am} + L_{am} \frac{di_{am}}{dt}$$
$$u_g = R_{fm} i_{fm} + L_{fm} \frac{di_{fm}}{dt}$$
$$e_{am} = C_{em} \Phi_m n_m \tag{30}$$

$$\left(C_{mn} \Phi_m i_{am} - M_0 - Mz\right) = \frac{375}{GD^2} \frac{dn_m}{dt} \tag{31}$$

$$i_g = i_f + i_{RP} + i_{CP} + i_L + i_R + i_{fm} + i_{am}$$
$$\Phi_m = F_f\left(i_{fm}\right) \tag{32}$$

where Φ_m is the flux of motor. The relation between Φ_m and the exciting current, i_{fm}, can be calculated according to machine size or through the experiment. The significance of the other symbols is shown in Fig. 6.

7. SAMPLE CALCULATION

The battery has the function of absorbing and stabilising the change of system voltage. If one wants to know the acuity of possible voltage change of an electrical system in a military vehicle, the calculation can be carried out after the battery is got rid of. Taking example for the motor load suddenly cut into system, carry out numerical computing.

The program flow chart for calculation when the load is suddenly cut into system, is shown in Fig. 7.

Let the motor suddenly cut into system. When the motor does not rotate, the initial conditions are $n_m = e_{am} = i_{am} = 0$. According to the initial value

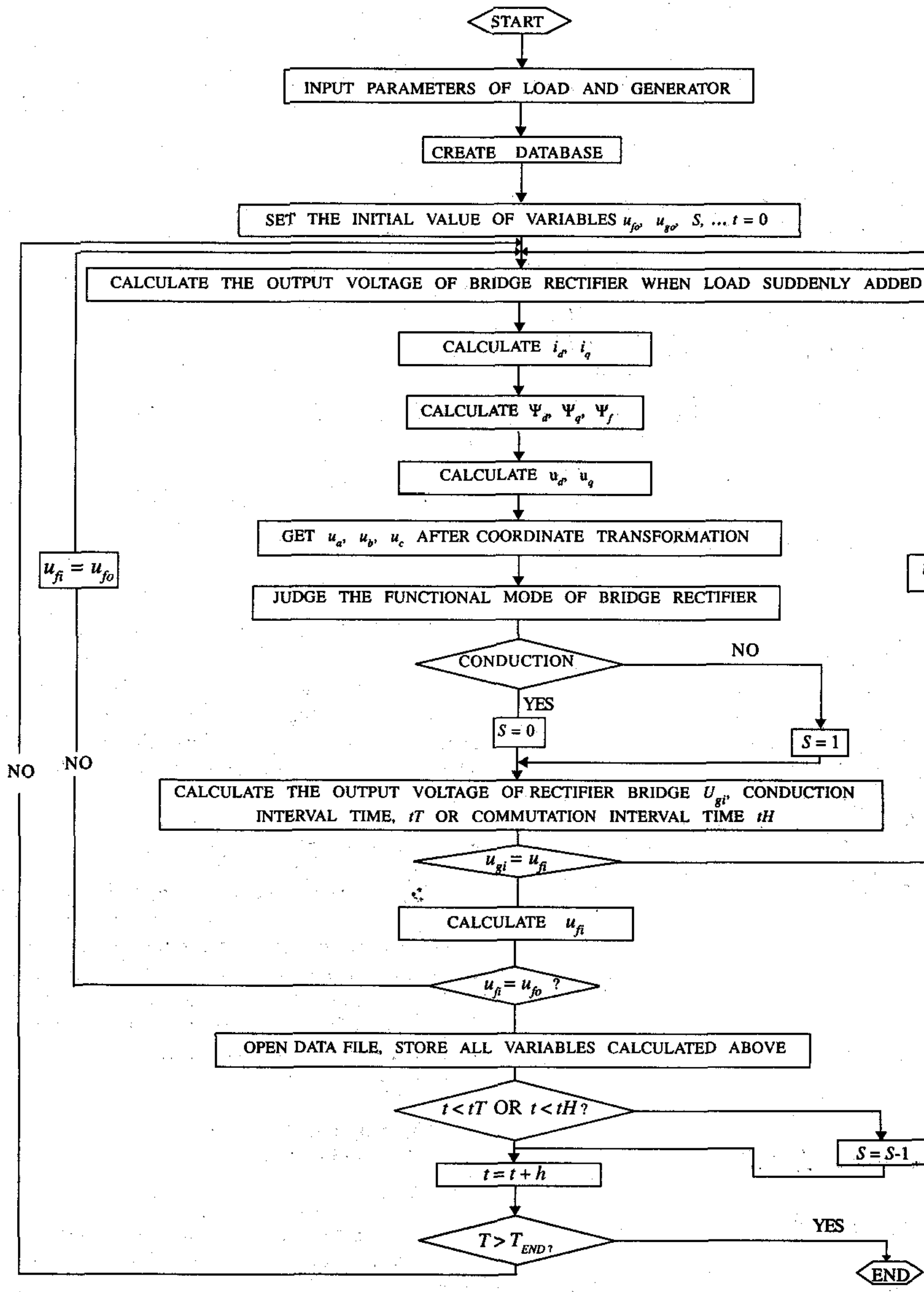

Figure 7. Program flowchart for calculation

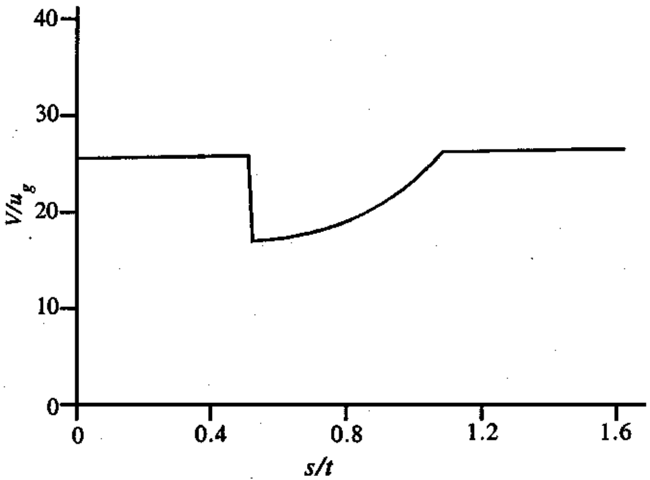

Figure 8. Surge calculated when vehicle system operates with generator, only, i.e., no battery.

of an electrical system, u_a, u_b, u_c, i_g, i_m can be calculated. In terms of the running conditions listed in Tables 1 and 2, the whole functional mode and mode transfer of the rectifier can be confirmed and u_g and u_f can be calculated.

Comparing these with the initial values, iterate and approach gradually until they are equal to finish a calculation step. According to the transfer law of modes affirmed by Fig. 3, the next variable of the whole functional mode is calculated. The variables of mode transfer are calculated one by one until conclusion meet request. When the silicon-rectifying generator GFT-6000 of electrical system in a military vehicle is cut suddenly with the amplidyne set KZ170 load, the surge calculated is shown in Fig. 8 and the practical result measured is shown in Fig. 9.

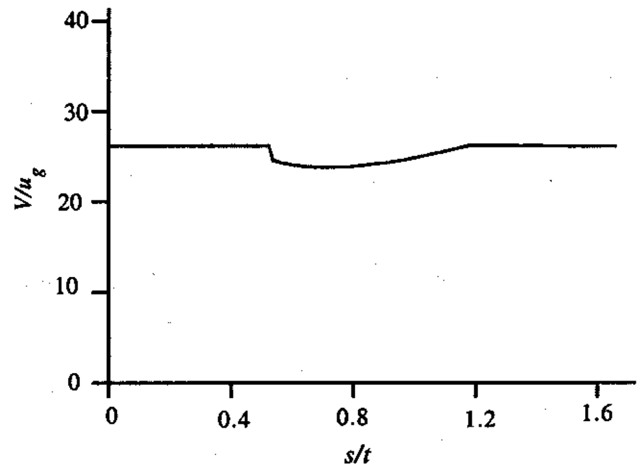

Figure 10. Surge calculated in the combined generator-battery power supply.

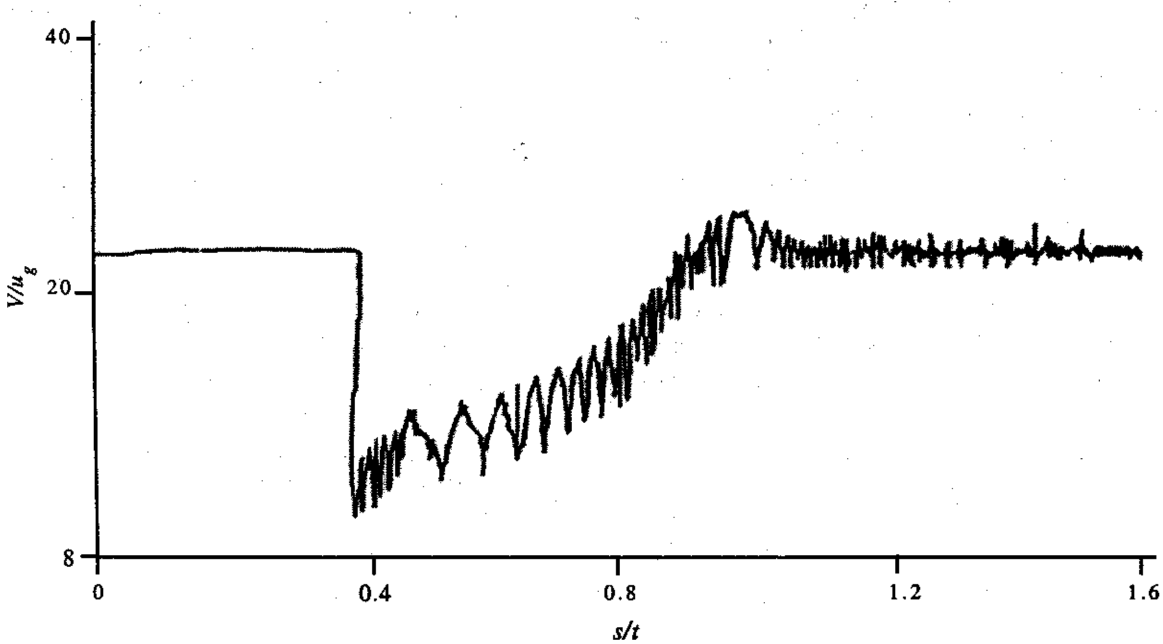

Figure 9. Surge measured when vehicle system operates with generator only, ie, no battery

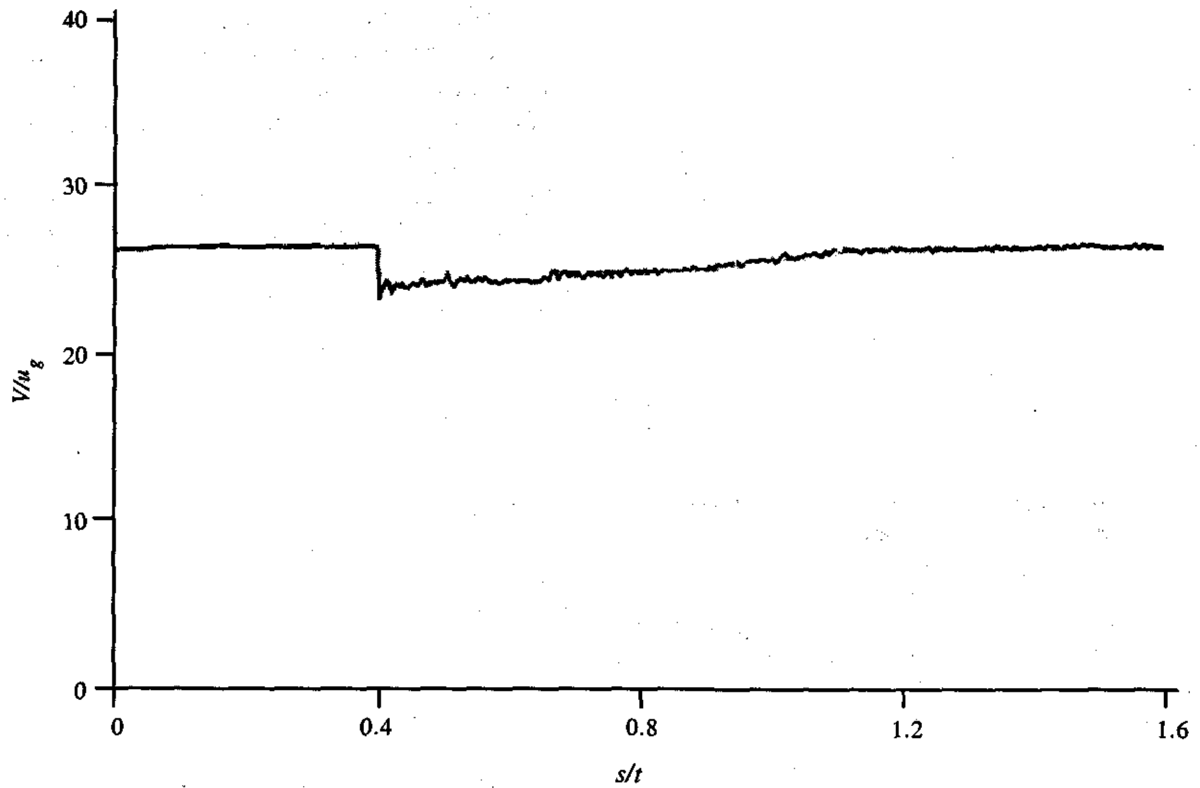

Figure 11. Surge measured in the combined generator-battery power supply

The surge calculated is shown in Fig. 10 when the load is suddenly cut into the combined generator-battery system.

The practical result measured is shown in Fig. 11. In addition, it is obvious that surge peak voltage understood reduces from 50 per cent to 10 per cent in the combined generator-battery system, which shows fully that the battery can absorb surge and make system voltage stabilized.

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