



# Report Documentation Page

Form Approved  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>JUN 1985</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Analysis Of A Pulsed Power System Containing Rotating Machine</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Los Alamos National Laboratory Los Alamos, New Mexico 87545</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>					
14. ABSTRACT <b>Several hundred megajoules of energy lasting for several seconds are required for magnetic fusion experiments. Such high energy can be stored as inertial energy in an alternator which is brought up to speed slowly. The alternator is then discharged through a thyristor converter to magnets which produce and sustain the plasma. A major portion of the inertial stored energy, for reversed field pinch experiments in Los Alamos, will be dissipated in charging the magnetizing coil to produce the plasma arc. The plasma is then sustained, during the flat-top period, by energizing the magnetizing coil in the reverse direction. To hold the plasma current constant at the required level, the output voltage of the converter must be held at a prescribed level by controlling the firing angle of the thyristors. The paper discusses the possibility of using the same converter for both the magnetizing and the flat-top periods. It also analyzes the electrical requirements that will be imposed on the alternator and the converter.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>SAR</b>	18. NUMBER OF PAGES <b>4</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

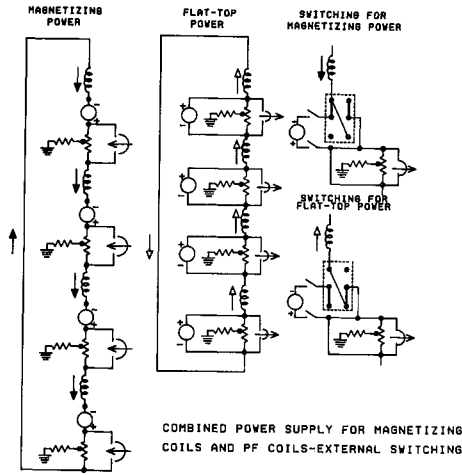


Fig. 2 Combined power supply for magnetizing and flat-top periods: External switching.

Each of the four sections of the flat-top power supply is composed of three modules, each module comprising four three-phase, full-wave thyristor bridges connected in parallel. During charging of the magnetizing winding, the three modules are connected in parallel; they are connected in series during flat-top operation. The external connection for the changeover is performed by two disconnect switches: a single-pole, single-throw switch and a double-pole, double-throw switch for each of the four sections. The intermodular connection for series/parallel operation is performed by two double-pole, double-throw disconnect switches. The thyristors will be blocked during the operation of these disconnect switches so that no power will be interrupted by these switches.

#### Analysis of the Magnetizing Period

##### Modeling of Generator

Initially the energy is stored entirely in the rotational inertia of the generator, its no-load losses being supplied through its prime mover by the power drawn from the electric utility system. Once the load is connected to the generator, both its speed (and frequency) and terminal voltage will decrease. The speed decreases because part of the inertial stored energy is converted into electrical energy during the experiment; the available voltage to the load decreases partly because of the decrease in generator speed and partly because of the voltage drop internal to the generator.

If the magnetizing period is divided into small time steps,  $t_s$ , then

$$dq = -(pn + v \cdot i) \cdot t_s,$$

$$q(t_2) = q(t_1) + dq, \text{ and} \quad (1)$$

$$f(t_2) = f_0 \sqrt{q(t_2)/q_0},$$

where  $pn$  = no-load losses of the generator,  $v, i$  = dc load voltage and current during  $t_s$ ,  $q(t_1)$ ,  $q(t_2)$  = generator inertial energy at  $t_1$  and  $t_2$ ,  $f(t_2)$  = generator frequency at  $t_2$ , and  $f_0, q_0$  = initial frequency and

stored energy of generator. The dc load current at  $t_2$  can be calculated from

$$di = (v - r \cdot i) \cdot t_s / \lambda; \quad i(t_2) = i(t_1) + di, \quad (2)$$

where  $r, \lambda$  = load resistance and inductance and  $i(0) = 0$ . The calculation of the dc load voltage  $v$  requires the knowledge of the electrical characteristics of the generator and of the converter. This will be discussed later.

The electrical characteristics of the generator were derived in accordance with Park's theory [1]. The generator internal voltage can be computed once its field current and speed are known. The generator terminal voltage is computed by subtracting the various impedance drops, internal to the generator. Figure 3 shows the phasor diagram of the generator voltages.

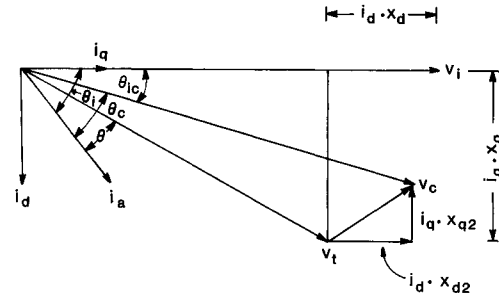


Fig. 3 Phasor diagram of generator voltages.

The voltage  $v_c$  in Fig. 3 is the voltage behind the "commutating" reactance. The commutating reactance is defined as that reactance per phase during the interval current is transferring from one rectifier leg to another. During this short interval, the subtransient reactances of the generator are significant. Therefore, the voltage drop across these reactances  $vdq_2$  is vectorially added to the generator terminal voltage  $v_t$  to determine  $v_c$ , e.g.,

$$\begin{aligned} vdq_2 &= id \cdot xd_2 + j \cdot iq \cdot xq_2 \\ &= ia \cdot \sqrt{(xd_2 \cdot \sin \theta)^2 + (xq_2 \cdot \cos \theta)^2} \\ &= ia \cdot xc_g, \end{aligned} \quad (3)$$

where  $xd_2, xq_2$  are the subtransient direct- and quadrature-axis reactances of the generator, and  $xc_g$  is the commutating reactance of the generator.

It is known that on sudden short circuit or sudden application of load to a generator, the internal reactances of the generator change from low values at the beginning of the period to higher steady-state values at the end of the period. To accommodate such change in the generator reactances, equivalent direct- and quadrature-axis reactances were assumed, which are given by

$$1/x_{d'e} = (1/\omega) \cdot [(1/\lambda d) + \{(1/\lambda d_1) - (1/\lambda d)\} \cdot t_1 + \{(1/\lambda d_2) - (1/\lambda d_1)\} \cdot t_2], \quad (4a)$$

$$1/x_{q'e} = (1/\omega) \cdot [(1/\lambda q) + \{(1/\lambda q_1) - (1/\lambda q)\} \cdot t_3 + \{(1/\lambda q_2) - (1/\lambda q_1)\} \cdot t_4],$$

$$\begin{aligned} t_1 &= \exp(-t/td_1); t_2 = \exp(-t/td_2), \\ t_3 &= \exp(-t/tq_1); t_4 = \exp(-t/tq_2), \end{aligned} \quad (4b)$$

where  $\lambda_d, \lambda_q$  = direct- and quadrature-axis synchronous inductances,  
 $\lambda_{d1}, \lambda_{q1}$  = direct- and quadrature-axis transient inductances,  
 $\lambda_{d2}, \lambda_{q2}$  = direct- and quadrature-axis subtransient inductances,  
 $td_1, tq_1$  = direct- and quadrature-axis transient time constants, and  
 $td_2, tq_2$  = direct- and quadrature-axis subtransient time constants.

#### Modeling of Load and Converter

The load is the magnetizing winding which consists of a resistance and an inductance, connected in series. Electrically, a continuously decreasing dc voltage (converter output) charges an RL-circuit exponentially to a specified current level.

A 12-pulse converter consists of a bank of three-winding wye/wye/delta transformer and two three-phase full-wave thyristor bridges, each connected to one of the two secondaries of the transformer. The analysis will be the same if the three-winding transformer is replaced by two wye/wye and wye/delta transformers.

The thyristors in the converter conduct fully, i.e., the firing angle is zero during the magnetizing period. The modeling of converter closely follows the theory of conversion [2], with some modifications. As a 12-pulse converter was assumed, the ac line current  $i_a$  is given by [2], [3]

$$i_a = (2/6/\pi) \cdot i \cdot \left[ \frac{1 + \cos \delta}{2 \cdot \eta \cdot \cos \theta_i} \right], \quad (5)$$

where  $i$  = dc load current,  
 $\delta$  =  $\arccos(1 - i/is)$   
 $is = 0.1949 \cdot v_c / (f \cdot \lambda_c)$ ,  
 $\lambda_c$  = commutating inductance of the ac system,  
 $\theta_i = \arctan \{ (2\delta - \sin 2\delta) / (1 - \cos 2\delta) \}$ , and  
 $\eta$  = converter efficiency.

A second modification, because of the 12-pulse conversion, is that the commutating reactance of the generator seen from the converter is half of the generator actual commutating reactance [4], i.e.

$$x_c = (x_{cg}/2) + x_t, \quad (6)$$

where  $x_c$  is the total commutating reactance of the system, and  $x_t$  is the transformer commutating reactance.

The voltage behind the commutating reactance  $v_c$  and the dc load voltage  $v$  are determined iteratively at each time step  $t_s$ , starting from their initial values at no load for  $t = 0$ , as follows:

$$v_{co} = v_g / nm \cdot \sqrt{3}; v_o = 3\sqrt{2} \cdot v_g / \pi \cdot nm, \quad (7)$$

where  $v_g$  is the generator line-to-line rms voltage at no load, and  $nm$  is the voltage transformation ratio of converter transformer for the magnetizing period.

The various voltage phasors and their corresponding angles of Fig. 3 can be constructed, by trigonometric manipulations, at each time step, starting with the initial values of  $v_c$  and  $v$  (eq. 7) and  $i(t=0) = 0$ ,  $\theta_{ic}(t=0) = 0$ , remembering that the generator internal voltage  $v_i$  is reduced at each time step in proportion to its frequency, i.e.,

$$v_i = (f/f_o) \cdot (v_g / nm \cdot \sqrt{3}) \quad (8)$$

#### Analysis of the Flat-Top Period

Once the magnetizing coils are charged to the required current, the generator with the converter is disconnected from the load, and the vacuum circuit breakers CB (Fig. 1) are opened to initiate the plasma. Once the plasma is formed, energy must be supplied to the magnetizing coil to compensate for the losses in the plasma resistance, to keep the plasma current constant. The converter output voltage must equal the plasma voltage drop to keep the plasma current constant. The firing angle of the thyristors in the converter must be varied to accomplish this.

The generator model is the same as for the magnetizing period. However, the models for the load and the converter are different from those for the magnetizing period.

#### Modeling of Load and Converter

The simplified schematic of the load is shown in Fig. 4. The following are specified: 1. the load voltage  $v$ , and 2. the plasma current  $i_p$ , e.g.,

$$v = i_p \cdot r_p \cdot nmc, \text{ and} \quad (9)$$

$$i_p = i_{po}$$

where  $i_{po}$  = initial plasma current, and  $nmc$  = number of turns of the magnetizing coil. The converter output current  $i$  is found by analyzing Fig. 4,

$$\begin{aligned} i &= (i_{po}/nmc) \cdot [\exp(-a_2 \cdot t) - \exp(-a_1 \cdot t)] + (v/nmc^2 \cdot r_l) \cdot \\ &[1 - \exp(-a_1 \cdot t)] + (v/nmc^2 \cdot r_p) [1 - \exp(-a_2 \cdot t)], \end{aligned} \quad (10)$$

where,  $a_1 = r_l/\lambda_l$ , and  $a_2 = r_p/\lambda_p$ .

Several "fictitious" terms are then defined in order to determine the required firing angle of the thyristors in the converters [2].

$$v_o = 2.3391 \cdot v_c$$

$$is = v_o / (12 \cdot f \cdot lcf); c = i/is \quad (11)$$

$$b = v/v_o; b_1 = b + 0.5 \cdot c; b_2 = b - 0.5 \cdot c$$

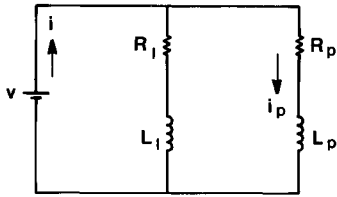
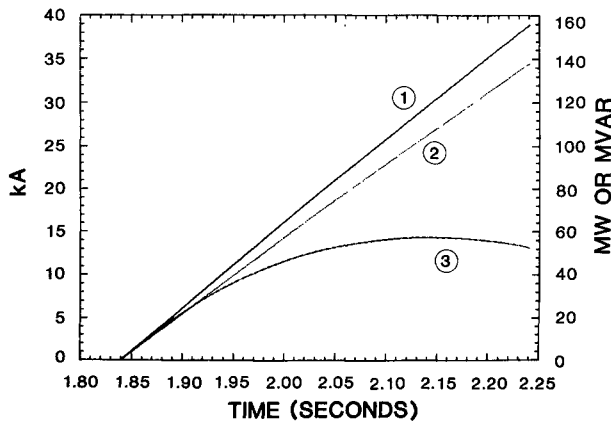


Fig. 4 Simplified schematic of load during flat-top period.  $R_p$ ,  $L_p$  = plasma resistance and inductance.

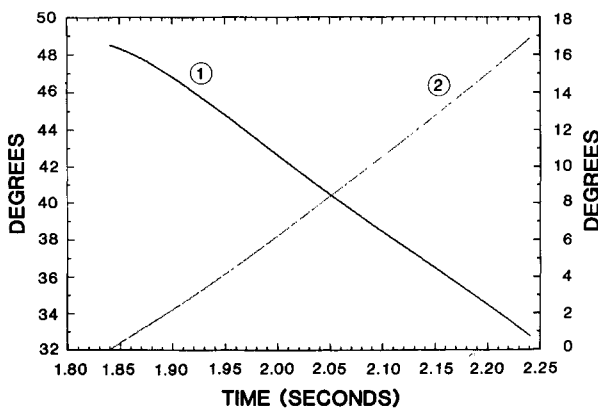
where  $v_c$  = voltage behind the commutating inductance, and  $\lambda_{cf}$  = commutating inductance in the flat-top period. From eq.(11), the firing angle  $\alpha$ , and the overlap angle  $u$  can be determined,

$$\alpha = \arccos(b1); u = \arccos(b2) - \alpha \quad (12)$$

The computation of the voltage behind the commutating reactance  $v_c$ , and the converter output (active and reactive powers) is similar to that for the magnetizing period.



(a)



(b)

Fig. 5 Profiles of variables during flat-top period. (a) 1. converter output current, 2. converter power, 3. converter reactive power. (b) 1. converter firing angle, 2. overlap angle.

Figure 5 shows the profiles of some of the variables during the flat-top period.

### Discussion

Generally, the commutating reactance of a synchronous machine is assumed to be either the arithmetic or the geometric mean of  $x_{d2}$  and  $x_{q2}$ . This is not correct. The effects of armature reaction on the generator field flux are twofolds: 1. the direct-axis component of armature current demagnetizes the field flux, and 2. the quadrature-axis component cross-magnetizes the field flux. The resultant effect of armature reaction is a voltage drop internal to the machine. As the demagnetizing and the cross-magnetizing effects of armature current are at quadrature to each other, the two components of internal voltage drop must also be at quadrature to each other. Therefore,  $x_{cg}$  of Eq. (3) should be the correct form of the synchronous-machine commutating reactance.

Once the load characteristics are known, the pulsed power system can be optimized with the help of the proposed analysis. For instance, the reactive power requirement can be minimized by proper choice of series/parallel combination of the converter modules and the voltage ratio of the converter transformers. Whether the plasma current is held constant during the flat-top period for a specific choice of the power supplies can also be easily ascertained.

### Conclusions

1. A new concept for the synchronous-machine commutating reactance is presented.
2. A simple and fast but accurate method of analysis is developed to design a pulsed power system containing a rotating machine.
3. The use of the same power supply for both the magnetizing and the flat-top periods is economically attractive, and technically feasible, particularly because the changeover switches do not have to interrupt power.

### Acknowledgment

The author gratefully acknowledges the valuable advice and encouragement from Dr. R. F. Gribble during this study.

### References

- [1] C. Concordia, Synchronous Machines Theory and Performance. John Wiley & Sons, New York. 1951.
- [2] E. W. Kimbark, Direct Current Transmission. Wiley-Interscience, New York. 1971.
- [3] W. E. Newell, "Analysis of the TFTR Toroidal Field Power Supply and its Interactions with Other Loads." Proc. Sixth Symposium on Engineering Problems of Fusion, IEFEE Pub. No. 75CH1097-5-NPS, November 18-21, 1975.
- [4] P. C. S. Krishnayya, "Stresses on Generators and Transformers of Block and Double-Block Connections Proposed for HVDC Power Station Infeed," Proc. International Conference on High Voltage DC and/or AC Power Transmission, IEE (England), London, 19-23 November 1973, pp. 279 - 286.