Simulation of the Distance Relay Using EMTP MODELS

J.Y. Heo*, C.H. Kim* and R.K. Aggarwal**

Abstract - Digital technology has advanced significantly over the years both in terms of software tools and hardware availability. It is now applied extensively throughout many area of electrical engineering including protective relaying in power systems. Digital relays have numerous advantages over traditional analog relays, such as the ability to accomplish what is difficult or impossible using analog relays. Although non real-time simulators like PSCAD/EMTDC are employed to test the algorithms, such simulations are disadvantaged in that they cannot test the relay dynamically. Hence, real-time simulators like RTDS are used. However, the latter requires large space and is very expensive.

This paper uses EMTP MODELS to simulate the power system and the distance relay. The distance relay algorithm is implemented and the distance relay is interfaced with a test power system. The distance relay's performance is then assessed interactively under various fault types, fault distances and fault inception angles. The test results show that we can simulate the distance relay effectively and we can examine the operation of the distance relay very closely including its drawbacks/limitations by using EMTP MODELS. Equally important, this approach facilitates any changes that need to be carried out in order to enhance the Distance Relay under test/examination.

Keywords: Distance Relay, EMTP, EMTP MODELS, Relay Model, Digital Simulation, Protection, Power System

1. Introduction

The first protective relay ever designed was of the EM (electro-mechanical) style and it then progressed to the solid-state relay style. Such relays were of the analog type and contained algorithms that were realized by the hardware composed of many mechanical and electronic components. However, the functions of these relays have been limited by the difficulty and the complexity of analog signal processing. Digital technology on the other hand provides the flexibility and increased functionality in protective relays that is difficult to be achieved in analog relays [1, 2].

Most functions of digital relays are realized by the program code of a microprocessor. The large number of functions and complexity of the digital relay programs requires the necessary tools to verify and test the algorithms.

General machines based on microprocessors can be relatively easily tested by executing the particular developed program. However, the protective relay hardware cannot be easily tested on an actual power system. Although the developed relay algorithms have been tested with the waveform signals generated by non real-time simulators like PSCAD/EMTDC, this approach has the disadvantage of not being able to be tested dynamically. Some researchers have used real-time simulations like RTDS (real time digital simulator) to test the relay algorithm dynamically, but this method requires additional hardware, which is rather costly [3-5].

This paper presents a technique whereby the algorithm of the distance relay is verified and tested by EMTP MODELS dynamically.

2. EMTP MODELS

2.1 EMTP MODELS

The EMTP (electromagnetic transient program) is the simulation tool used to simulate the electro-magnetic transients phenomenon, and it is one of the most widely used programs throughout electric utilities [6-9]. However, open-loop simulation can be used only in the static state of a power system or in the preset sequential state. That is, it cannot imitate the system in response to the result of the simulation during the simulation process. The system diagram of EMTP operation without MODELS is shown in Fig. 1. The preset sequence data of Fig. 1 changes the state of the EMTP power system, and the voltage and the current

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Received July 10, 2003 ; Accepted February 18, 2004

of the power system is simulated according to the changed state of the power system. Its results are recorded in the computer file and the play-back waveforms are utilized by the relay model. The EMTP is used as a signal generator. It is referred to as open-loop (also called play-back) simulation [10].

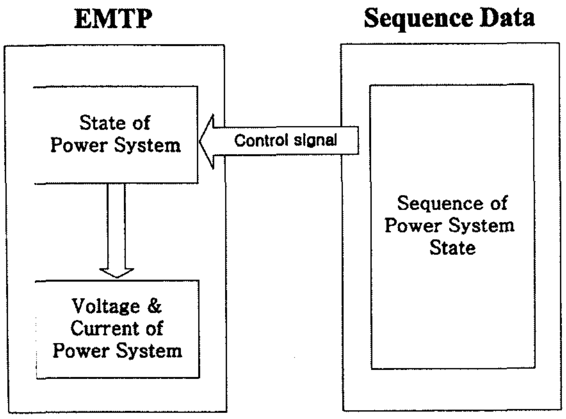


Fig. 1 Operation of EMTP without using MODELS

MODELS is a symbolic language interpreter for the EMTP that has recently gained popularity for the electro-magnetic transients phenomenon modeling. MODELS provides the monitoring and controllability of power systems as well as some further algebraic and relational operations for programming. MODELS is able to dynamically alter the states of the power system in response to the simulated results of the EMTP power system. The system diagram of the EMTP MODELS operation is shown in Fig. 2. The voltage signals and the current signals of the EMTP power system enter the input of MODELS. These signals are processed by the program coded with MODELS and the output signals by MODELS change the states of the EMTP power system. This process is repeated until the simulation is complete. MODELS makes it possible to simulate the interaction between the power system and the measuring or control system. This is referred to as closed-loop simulation [10].

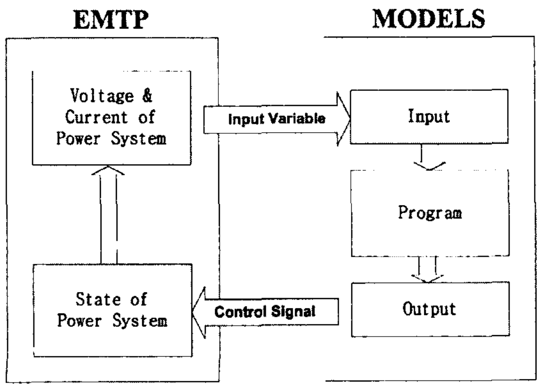


Fig. 2 Operation of EMTP using MODELS

Fig. 3 illustrates the simulation process in the time domain. The variable T in Fig. 3 is the time of the simulation and the ΔT is the size of the time step in the simulation. EMTP (T) is the function that it simulates on T, and MODELS (T) is the function that it runs on the pre-composed program of MODELS. The MODELS execution time is the same as that of the EMTP simulation, and this indicates that MODELS is able to measure the state of the power system and to control the power system more precisely [6]. MODELS enables the EMTP to be used flexibly.

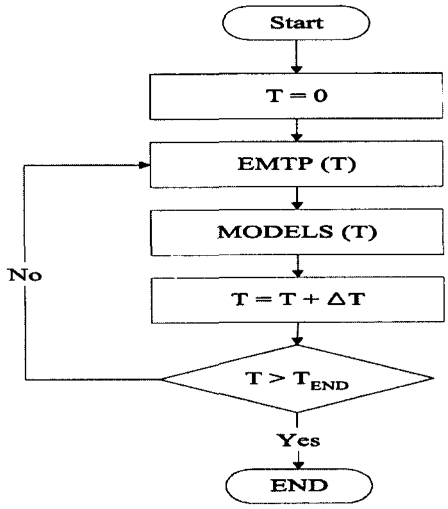


Fig. 3 Operation of EMTP MODELS in time domain

2.2 Implementation of Distance Relay By MODELS

Fig. 4 shows the system diagram in which the distance relay is constructed by MODELS. The signals of the node voltage values and the node current values are sent to the MODELS inputs and the parameter settings are used in the MODELS algorithm. The fault is detected by the MODELS algorithm. If the fault is detected and the trip of the circuit breaker is determined by the algorithm, then MODELS sends the opening command of the EMTP switch to the EMTP's main simulation. The states of the power system,

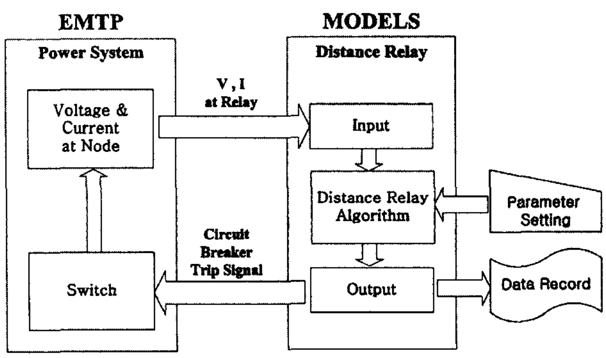


Fig. 4 System diagram of relay structure by MODELS

3. Structure of Distance Relay

The distance relay structure used in this paper is shown in Fig. 5. The inputs of the system are the voltage values and the current values of each phase, and the outputs of the system are the trip signal of the circuit breaker and the fault type. The parameter setting values determine the relationship between the inputs and the outputs, and their values must be changed according to the status of the power system. Line impedance, impedance characteristics and timer delay value can be included in the parameter setting values [10]. The signal processing module generates signals of any apparent impedance, the rms values of the current's symmetrical components, the derivative values of voltage and the derivative values of the impedance phasor angle. The signals generated in the signal processing module are analyzed in the fault detection module to detect faults. The parameter values control each module.

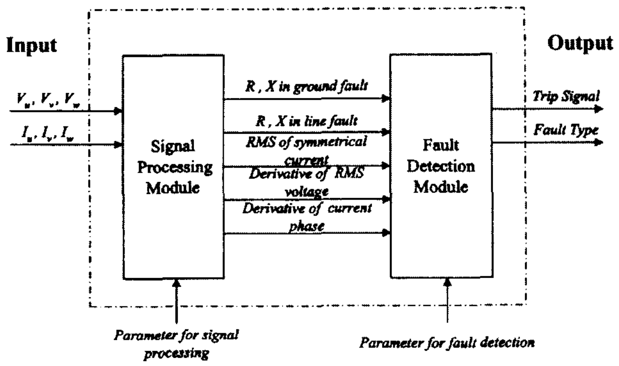


Fig. 5 Structure of distance relay

3.1 Signal Processing Module

The input signals of the voltage and the current in each phase are transformed into signals that are needed in the fault detection module. The signals that can be used in the fault detection module to detect a fault, are the instantaneous values of the voltage and the current, the rms values of the voltage and the current, the symmetrical components of the current, the apparent impedance and the derivative of the impedance angle in both the line-to-line and the line-to-ground faults, the frequency of the voltage and the current.

3.2 Fault Detection Module

The processed signals in the signal processing module are transferred to the fault detection module. The signals are analyzed by the algorithm in the fault detection module. The algorithm decides whether it trips a circuit breaker or not.

One of the methods employed to detect the type of fault involves using symmetrical components of a current. Table 1 shows that the symmetrical components of a current vary according to the types of faults. This can be used to determine which type of fault occurs. However, it does not provide any information to determine which phase is faulted. The methods to determine the faulted phase are given as [11-13]:

1) Method to use over-current in phase.
2) Method to use apparent impedance.
3) Method to use apparent impedance and angle of impedance.

Table 1 Symmetrical component of current according to fault types

	Pos.-sequence current	Neg.-sequence current	Zero-sequence current
3-line fault	$\frac{E}{Z_1}$	0	0
Double line-to-line fault (L2-L3)	$\frac{E}{Z_1+Z_2}$	$-\frac{E}{Z_1+Z_2}$	0
Double line-to-ground fault (L2-L3-E)	$\frac{(Z_2+Z_0)E}{Z_p}$	$-\frac{Z_0E}{Z_p}$	$-\frac{Z_2E}{Z_p}$
Single line-to-ground fault (L1-E)	$\frac{E}{Z_q}$	$\frac{E}{Z_q}$	$\frac{E}{Z_q}$
$Z_p = Z_1Z_2 + Z_2Z_0 + Z_0Z_1$ $Z_q = Z_1 + Z_2 + Z_0$			

* Z_0, Z_1, Z_2 : Zero, Pos., Neg.-sequence component of line impedance to fault location, E : Phase voltage of source

After detecting the fault type and the faulted phase, the apparent impedance is calculated according to the fault type and it is then applied to the impedance characteristic to determine whether the fault is within a protected area or not, and to set the delay time of the trip.

The overall structure of the fault detection module is shown in Fig. 6. In Fig. 6, the zero-sequence component of current I0 is used to determine whether the fault is a line-to-ground fault or a line-to-line fault, and the algorithm of the impedance characteristics decides the faulted phase and the trip of the circuit breaker.

The algorithms of the impedance characteristics are different according to the fault zone. When the apparent impedance enters zone 1, the trip signal is generated immediately, whereas the trip signal is generated after the delay time in zones 2 and 3. The algorithms operate independently and so they function correctly when the apparent impedance oscillates between two zones [8].

The algorithm for a line-to-line fault can be constructed in a manner similar to the algorithm for a line-to-ground fault, but the advanced algorithm to prevent mal-trip due to out-of-step, power swing and voltage instability is used in this paper [14]. Voltage instability and transient instability are detected using the derivative of the voltage and impedance angle.

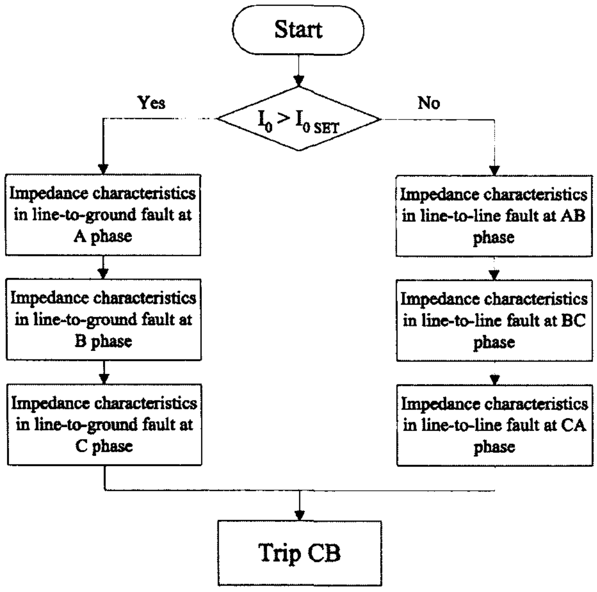


Fig. 6 Flowchart of fault detection module

4. Simulation Results

4.1 Simulation Method

A set of simulation tests were carried out in the test model of a power system, as shown in Fig. 7. The power system model is connected with the distance relay model designed with EMTP MODELS. The transmission system modeled is comprised of a total line length of 500km.

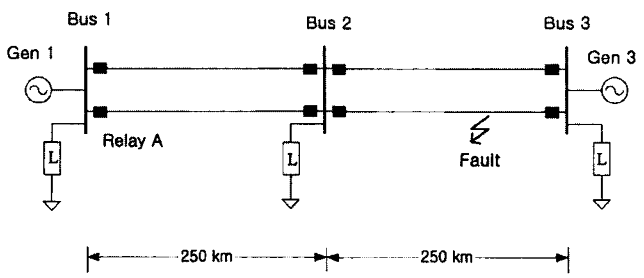


Fig. 7 Model of power system

The conductor size is ACSR 477MCM 240 and the electrical constants are shown in Table 2.

Table 2 Data of transmission line and generator source

		R [Ω/km]	L [Ω/km]	C [μF/km]
Line impedance	ZSC	0.3434	1.3158	0.0052
	PSC	0.1342	0.4765	0.0090
	NSC	0.1342	0.4765	0.0090
Source impedance	PSC		18.285	

* ZSC (Zero-Sequence Component), PSC (Positive-Sequence Component), NSC (Negative-Sequence Component)

The model of the distance relay is connected to the model of the power system on relay A of bus 1. A simulation is carried out for various fault types, fault inception angles and distances at a position between buses 2 and 3, and operation of the distance relay is examined closely.

Table 3 Parameter setting values of relay's zone

	Ratio [%]	Impedance [Ω]	Impedance [p.u]	Delay Time[s]
ZL (Line)	100	33.55+j119.13	0.14+j0.50	
Z1 (Zone1)	80	26.84+j95.30	0.11+j.40	0
Z2 (Zone2)	120	40.26+j142.95	0.17+j0.60	0.2
Z3 (Zone3)	440	147.62+j524.2	0.63+j2.21	2

Table 4 Parameter setting values of relay

	Setting value	Setting value
$\frac{dV}{dt}set$	-648 [kV /s]	-4.2 [p.u / s]
$\left\|\frac{d\Phi}{dt}set\right\|$	3000 [deg /s]	
I_0_SET	20.5 [A]	0.055 [p.u]
I_2_SET	80 [A]	0.213 [p.u]

Sample numbers per period are set to 12, and the impedance characteristic is the mho type. The setting parameters of relay's zone are indicated in Table 3. Zone 3 is set to 440% because under-reaching occurs in a double circuit line with infeed current [15, 16]. Other setting parameters like the result of the voltage threshold and impedance angle, and the zero-sequence and positive-sequence components of the current are shown in Table 4.

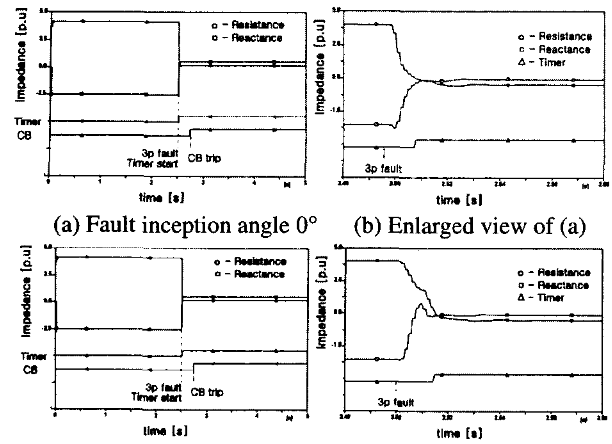
4.2 Simulation Of Distance Relay

In the simulation, the fault between bus 2 and bus 3 occur 2.5s after simulation initialization. The results of the simulation indicate that the relay model detects faults correctly and generates the trip signal.

4.2.1 Three Phase Fault

The apparent impedance of relay A, as well as the logic signals of the timer operation and the circuit breaker trip are shown in Fig. 8, when three phase fault occurs at a fault distance of 110% at the fault inception angles of 0° and 90°. Fig. 8 illustrates that the timer starts on fault inception and the trip signal are generated 0.2 seconds (zone 2 time) after the fault occurs.

Resistance and reactance are generated in the signal processing module, and the timer and CB trip signals are generated in the fault detection module using signals from the signal processing module. The fault is detected by the impedance algorithm in the case of a line-to-line fault. Fig. 8 shows that the timer start signal, that is the inner variable of the relay, can be investigated closely during fault occurrence.



(a) Fault inception angle 0° (b) Enlarged view of (a)

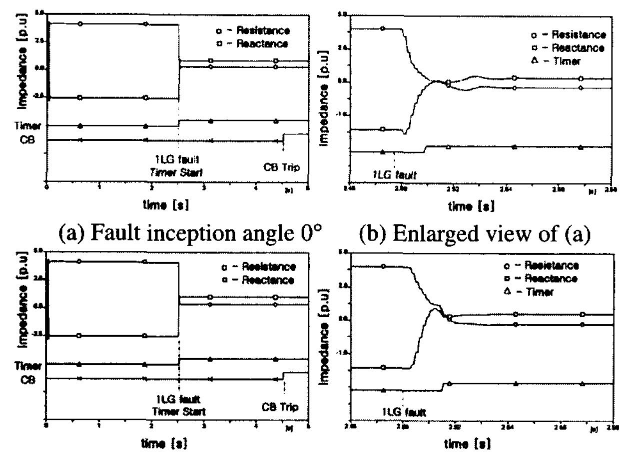
(c) Fault inception angle 90° (d) Enlarged view of (c)

Fig. 8 Result of dynamic simulation of distance relay using EMTP MODELS(3-phase fault, fault distance 110%)

4.2.2 single line-to-ground fault

The apparent impedance of relay A, the logic signal of the timer operation and the circuit breaker trip are shown in Fig. 9, when single line-to-ground fault occurs at a fault distance of 130% at fault inception angles of 0° and 90°. Fig. 9 shows that the timer starts at the occurrence of the fault and the trip signal is generated 2 seconds after the fault occurs (zone 3 time).

As in the case of the previously described 3-phase fault, all signals processed by the signal processing module or the fault detection module are monitored fully. The fault is detected by the impedance algorithm for a line-to-ground fault.

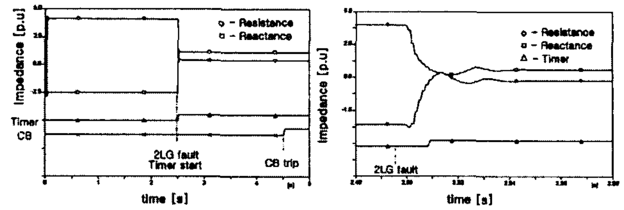


(a) Fault inception angle 0° (b) Enlarged view of (a)

(c) Fault inception angle 90° (d) Enlarged view of (c)

Fig. 9 Result of dynamic simulation of distance relay using EMTP MODELS (single line-to-ground fault, fault distance 130%)

4.2.3 Double Line-To-Ground Fault



(a) Fault inception angle 0° (b) Enlarged view of (a)

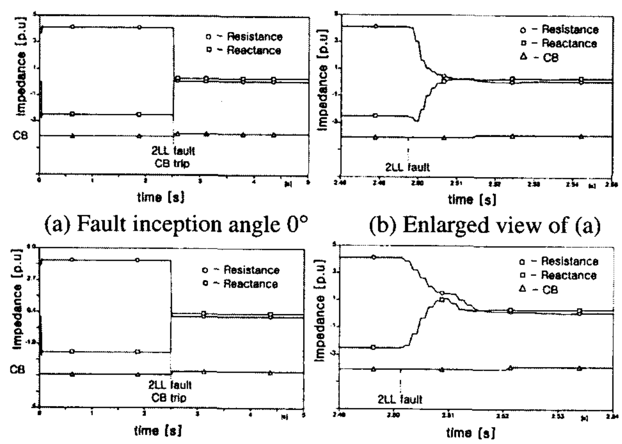
(c) Fault inception angle 90° (d) Enlarged view of (c)

Fig. 10 Result of dynamic simulation of distance relay using EMTP MODELS (double line-to-ground fault, fault distance 150%)

The apparent impedance of relay A, the logic signal of the timer operation and the logic signal of the circuit breaker trip are shown in Fig. 10, when a double line-to-ground fault occurs at a fault distance of 150% at fault inception angles of 0° and 90°. Fig. 10 shows that the timer starts on the occurrence of a fault and the trip signal is generated 2 seconds after the fault occurs.

4.2.4 Double Line-To-Line Fault

The apparent impedance of relay A, the logic signal of timer operation and the logic signal of the circuit breaker trip are shown in Fig. 11, when a double line-to-line fault occurs at a fault distance of 70% at fault inception angles of 0° and 90°. Fig. 11 demonstrates that once the fault occurs, the trip signal is generated.



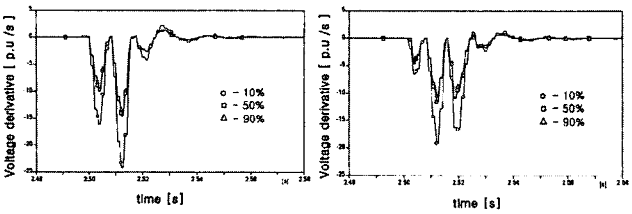
(a) Fault inception angle 0° (b) Enlarged view of (a)

(c) Fault inception angle 90° (d) Enlarged view of (c)

Fig. 11 Result of dynamic simulation of distance relay using EMTP MODELS (double line-to-line fault, fault distance 70%)

4.2.5 Derivative Of Voltage For A Three Phase Fault

The waveforms of the voltage derivative according to the fault distance are shown in Fig. 12, which indicates that the closer the fault distance, the smaller the minimum value.



(a) Fault inception angle 0° (b) Fault inception angle 90°

Fig. 12 Voltage derivative according to fault distance for 3-phase fault

5. Conclusions

This paper demonstrates that EMTP MODELS can be used to accomplish the following; simulate the distance relay, construct the algorithm of the distance relay by EMTP MODELS, and correctly operate the distance relay model.

Although EMTP MODELS cannot simulate real-time, it has the advantage that it is able to examine the inner operation of the distance relay and to simulate it more simply using a personnel computer. Using this approach, the detection of any bugs in the protection algorithm is facilitated. In this respect, in the actual relay using a microprocessor, it is always more difficult to trace the problems with the algorithm. The conclusions have been modified to include the following: The integrated model of the power system and the protective relay system for transmission lines (as described herein) is desirable for more efficient relaying algorithm development and improvement as well as for the evaluation of the existing algorithm in a closed loop manner; equally importantly, it provides better insight into the behavior of the algorithm.

Acknowledgements

The authors would like to acknowledge the financial and other support for this project provided by the Korea Science and Engineering Foundation(KOSEF). Project Number: 2000-2-30200-003-3

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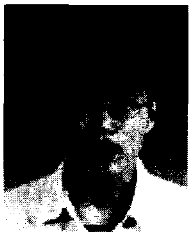

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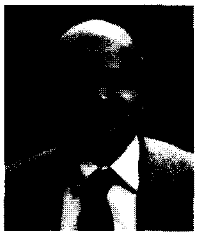

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