THE NEED FOR ULTRA-FAST FAULT CLEARING

by

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Introduction

Relays perform many functions. They protect transformers, buses and lines and any other equipment that is connected to an electrical system. There are hundreds of different kinds of relays that perform specialized services. The primary function of relays is to identify equipment failures and to isolate that equipment before the failure can propagate and cause failure of other equipment. Failure of other equipment could very likely lead to cascading outages and service interruption to large numbers of ultimate consumers of electric energy. This is, of course, the "motherhood and apple pie" concept of relaying.

As systems grow in their magnitude, we as engineers, must also grow to satisfy the growing needs of electric power consumers. Reliability of service to those needs has been a primary concern of relay engineers since the beginning of the electric power industry in the 1880's.

Many innovations in system protection have developed over the last 100 years of utility experience. Systems have grown from a single generator serving a small community to interconnections between communities and to transmission systems serving many communities in a geographical area. It wasn't until the early 1950's that the various systems of the Pacific Northwest were totally integrated into a regional transmission grid system.

Each stage of development required new technology in the protection of growing and increasingly interconnected systems. By the mid-1960's, the Pacific Northwest system, including Washington, Oregon Idaho, Western Montana and British Columbia, was interconnected with the California systems. Soon after that the electric power utilities in Wyoming, Utah, Colorado, Nevada, Arizona and parts of New Mexico, Missouri, and Texas interconnected with the western systems to form an integrated transmission network covering the western portions of the United States and Canada. Each new interconnection presented new challenges to the relay engineer. Systems could no longer be looked at individually. They had to be looked at with respect to their neighbors over an increasingly large geographic area. Faults on one system could suddenly impact systems hundreds of miles away.

Western Systems Coordinating Council

In order to evaluate the needs and benefits of improved switching facilities, it is necessary to look at the whole of interconnected power systems. The Bonneville Power Administration transmission system represents about 80 percent of the transmission facilities in the Pacific Northwest. However, they are a much smaller part of the broader transmission system represented by the Western System Coordination Council. Within the WSCC, all the power systems in parts or all of the fourteen western states and British Columbia are interconnected in a massive transmission network. That network extends over nearly 1.6 million square miles and represents about 51 percent of the land area in the contiguous United States. Electric service is provided to about 38 million people. There are 74,000 miles of transmission lines 115 kV and higher and 92,500 MW of installed generation capacity in the WSCC. The peak load in 1975 was 63,683 MW. It is estimated that the WSCC peak load will be about 120,000 MW by 1985. Frequently, generation resources are located 200 to 600 miles or more from load centers.

Load patterns in the WSCC range from heavy winter peaking in the northern portion to predominate summer peaking in the south. These patterns have led to extensive opportunities for transfer of energy, placing a heavy strain on the interconnected transmission system at different locations and different times of the year. Those transfer opportunities are augmented by the predominately hydro system in the Northwest where the availability of water depends on the whim of Mother Nature. That hydro system is usually capable of generating more power during the spring months than is necessary to serve Northwest loads. Consequently, surplus energy is available during parts of the year to serve loads on the southern systems.

Pacific Northwest-Southwest Intertie

The California Intertie consists of two 500-kV lines running from John Day Dam and interconnecting with several stations on the California systems as far south as Los Angeles. A critical substation, which will be referred to later, is Malin which is located near the Oregon-California border. An 800-kV d-c line also connects the Northwest directly with Los Angeles. Since the Intertie went into commercial operation in 1968, over 100 billion kilowatt hours of surplus Northwest energy has been sent to the southern systems. That energy has displaced about 170 million barrels of oil that would otherwise have been consumed for the production of electric energy.

Other Benefits of Interconnection

Another example of the benefits of interconnected system operation occurred when the Peace River plants, generating 1800 MW were suddenly lost to the Canadian system when two 500 kV lines were hit by severe icing and high winds. Emergency schedules were quickly established over the Intertie to supply support from as far away as

San Diego as well as from other WSCC systems. That outage, by the way, was greater than the outage that triggered the Northeast blackout of 1965.

Interconnected System Failure

Unfortunately, systems do not always perform as planned. The planned interconnected operation of the WSCC has failed on several occasions. For example, on April 7, 1976, one of the 500-kV Intertie lines relayed while the Malin Substation was abnormal due to circuit breaker maintenance. The remaining line relayed by out-of-step relays about four minutes later due to system oscillation. Northwest generator dropping and the islanding scheme between Utah and Arizona both failed to operate. Northwest frequency went to 60.9 Hz and Southwest frequency dropped to 59 Hz. Lines then relayed in Arizona and Utah and Southwest load shedding schemes dropped 1500 MW of load.

Reliability Criteria

Clearly, enormous benefits are attainable through interconnected system operation. But, there are disadvantages as well. Perhaps the greatest of these are the impacts that disturbances, such as faults, on one system can cause on another system. Soon after establishment of WSCC, it became apparent that standardized criteria for system design was necessary to maximize the benefits of interconnected system operation. Those criteria define the acceptable corrective action that any system should have to take as a result of a disturbance on another system. As a disturbance on one system will be reflected in varying degrees on other systems, the setting of limits of this effect on other systems is the objective of the criteria.

To accomplish that end, the member systems of the WSCC agreed on performance levels. The least severe performance level, allows post-disturbance line loadings and substation voltages to exceed normal limits but not emergency limits prior to system readjustment. It requires no remedial action or abnormal system performance on other systems except as agreed by the systems involved. An example of such a disturbance is normal clearing of a three-phase line fault while one generator is out of service. With that disturbance, no other system should have to take remedial action such as load or generation dropping, opening of interconnections or other lines or such action as system islanding. This means that the more common system disturbances should not cause instability in any of the WSCC interconnected systems. The WSCC reliability criteria also recognize that more severe, but less frequent disturbances may require remedial action.

Stability Consideration

The WSCC system can be looked at as two large rotating masses--one in the Pacific Northwest, and the other in the Southwest. They are connected by lines consisting of the Northwest-Southwest Intertie. The systems through Wyoming, Utah and Arizona also contribute to the interregional transfer of power. Disturbance in the Northwest can cause oscillations between the two rotating masses. They have, in the past, led to instability and opening of the interconnections. This, in turn, has caused remedial action on other systems in violation of the WSCC reliability criteria.

Remedial Action

The Northwest systems have employed a number of means to protect against instability of the Intertie and violation of the reliability criteria. Those include:

a. Automatic fast insertion of series capacitors in the two 500-kV Intertie lines.

b. Automatic dropping of Northwest generation for certain faults on the Intertie lines.

c. Modulation of power on the D-C Intertie line.

d. The dynamic braking resistor at Chief Joseph Dam.

e. High-speed fault clearing.

Item a acts to improve stability between the Northwest and Southwest through reduction of the Intertie transfer impedance. It has been shown that sudden reduction in transfer impedance during disturbances provides more stability margin than if the series capacitors are continually in service at a higher level of compensation.

Item b tends to balance Northwest generation and load in the event that Intertie loading is suddenly reduced. It must be accompanied by the use of spinning reserves or controlled load dropping on the southern system to insure continuity of service to loads.

Item c acts to insure that system oscillations between the Northwest and Southwest are damped. A growing oscillation could result in separation of the A-C Intertie lines.

Item d and e are transient stability controls which insure that the first swing following a disturbance does not exceed the synchronizing capability of the Intertie.

Effect of Fast Fault Clearing

Fast relaying (or fast fault clearing), is a very important means of improving stability. Items a through d above act to stabilize a system which has already begun to swing; whereas fast fault clearing will lessen the degree to which the system is accelerated. Fast fault clearing will reduce the amount of other control action necessary to maintain a secure system under transient conditions.

Rapid fault clearing has the greatest benefit at locations where a fault causes strong angular acceleration to nearby generators. In this case, a temporary area accelerating power, P_a, is caused by reduction in plant output due to voltage suppression during the fault. The change in average rotor speed for the plants in the faulted area is given by

$$\Delta W = \frac{P_a}{M} t_c \quad \text{radians/second} \qquad (1)$$

where M is the total area inertia constant in megajoule-sec/radian, t_c is the fault clearing time in seconds and P_a is the area accelerating power in MW. The larger the ratio of P_a to M the more rapid the fault clearing must be. If the ratio is relatively small, conventional fault clearing times are acceptable. The rotational kinetic energy introduced into the system by the fault is given by

$$K.E. = \tfrac{1}{2} I' \quad (\Delta W)^2 \quad \text{megajoules} \qquad (2)$$

where $I' = M/W_o$ is the rotational moment of inertia and W_o is synchronous speed in radian/second. By substituting equation (1) into equation (2), a relation between kinetic energy and fault clearing time is:

$$K.E. = \frac{P_a^2}{2W_o M} t_c^2 \qquad \text{megajoules} \qquad (3)$$

The rotational kinetic energy introduced into the system is, therefore, proportional to the square of the fault clearing time. In many cases, the generator angles at the time of fault clearing are very near a balanced power flow condition, but the kinetic energy introduced during the fault causes them to swing away from this condition during the ensuing transient response.

Rapid fault clearing is therefore of particular benefit at locations where a fault of longer duration will introduce excessive transient kinetic energy.

Effect of Fault Location

An example of the effect of fault location involves the lines radiating from Grand Coulee. A fault located within a few miles of the Grand Coulee 500-kV bus will cause far greater acceleration of the Grand Coulee generation than a fault located at mid-line. Stability studies conducted by BPA have indeed shown that high-speed fault clearing is only required for close-in faults. Faults located about ten or more miles from Grand Coulee can be cleared with conventional line relaying without introducing excessive swing.

Figure 1 depicts the effect of fast fault clearing for a three-phase fault located at the Grand Coulee terminal of the Raver 500-kV line. That line is presently under construction and is scheduled for energization in late 1977. The curves show the effect of decreasing the clearing time from four cycles to two cycles. The curves assume a one-cycle margin over the expected clearing time. The curves illustrate the generator angle response at Grand Coulee as compared to the angle on the Pittsburg bus in the San Francisco area. The response with two-cycle clearing is much less severe. Similar improvement has also been observed at other generators throughout the system.

WSCC Stability

The generator angle response at Grand Coulee, as shown in Figure 1, is indicative of the stability of the Northwest system with respect to the systems in the southern portion of the WSCC. In effect, fast clearing increases the amount of power that can be transferred to the southern systems. This is illustrated in Figure 2, which is a plot of fault clearing time versus loading on the two 500-kV Intertie lines for a constant degree of stability. The constant degree of stability is based on the minimum impedance during the swing that would be observed by an out-of-step relay at Malin. The curve shows that the Intertie can be loaded about 250 MW more for each cycle of reduced clearing time at Grand Coulee.

Benefit of Increasing Intertie Loading

During an average water year in the Northwest, the amount of incremental surplus energy that can be transferred over the Intertie amounts to about two gigawatt-hours per incremental megawatt of Intertie capacity. That number can vary from more than four to zero for any year depending on actual water conditions. On the average, then, a 250 MW increase in Intertie capacity amounts to 500 gigawatt-hours of additional surplus energy transfers. That energy would displace about 800,000 barrels of oil that would otherwise be consumed each year in oil-fired plants in the southern portion of the WSCC. That oil conservation would be proportionately larger if fault clearing time at Grand Coulee is decreased by more than one cycle. As stated earlier, oil conservation has exceeded 170 million barrels since the Intertie went into commercial operation in 1968.

Other Benefits of Fast-Fault Clearing

Fast-fault clearing also has a number of additional benefits such as:

- Reduced damage to insulators, conductor and hardware from flashovers.
- Reduced safety hazards to substation personnel and linemen from step and touch potentials.
- Reduced mechanical stress in major substation equipment, generators and turbines.
- Also, faster reclosure may be possible because of reduced ionization resulting from the arc.

Future Needs

Those, then, are today's needs for ultra-fast fault clearing. But, what about tomorrow's needs? Despite extensive conservation efforts, the demand for electric power will continue to grow. FPC projections indicate that a 5 percent growth rate through the end of this century is a conservative estimate. Based on that estimate, the demand for electric power will double every 14 years. By the end of this century, we will have to have about three and one-half times the amount of generating capacity that is presently installed. That power must be transmitted to load centers over increasingly higher capacity lines.

Concern about the environmental impacts of transmission lines is likely to restrict the number of lines that can be built. In many cases, those constraints will require rebuilding existing lines to higher capacity. The net result is likely to be a decrease in the amount of reserve transmission capacity available to protect against line outages. Transmission systems are likely to become weaker than they are today, compared to the amount of power they will have to transmit.

Those future trends behoove the electric utility industry to develop and employ sophisticated equipment to avoid deterioration of system reliability. Concern in this regard is highlighted by efforts of the U.S. Energy Research and Development Administration (ERDA). They are presently soliciting proposals for research effort to more fully identify the benefits of ultra-high speed relaying and its impact on transmission networks. At this point, it appears that the two strongest areas which would benefit from fast-fault clearing include:

1. Remote generation which is radially connected to large load centers, and,

2. Systems with large concentrations of load and generation interconnected by long transmission lines.

Both of these conditions are represented in the WSCC.

Conclusions

It is safe to assume that high-speed relaying and ultra-fast fault clearing will be with us for a long time to come. Within a few years we should see new and improved designs having greater assurance of reliable operation. Such high-speed devices, together with other engineering innovations, will facilitate the continued reliability of electric power systems.

FIGURE I

3 Ø FAULT AT COULEE ON THE RAVER 500KV CIRCUIT

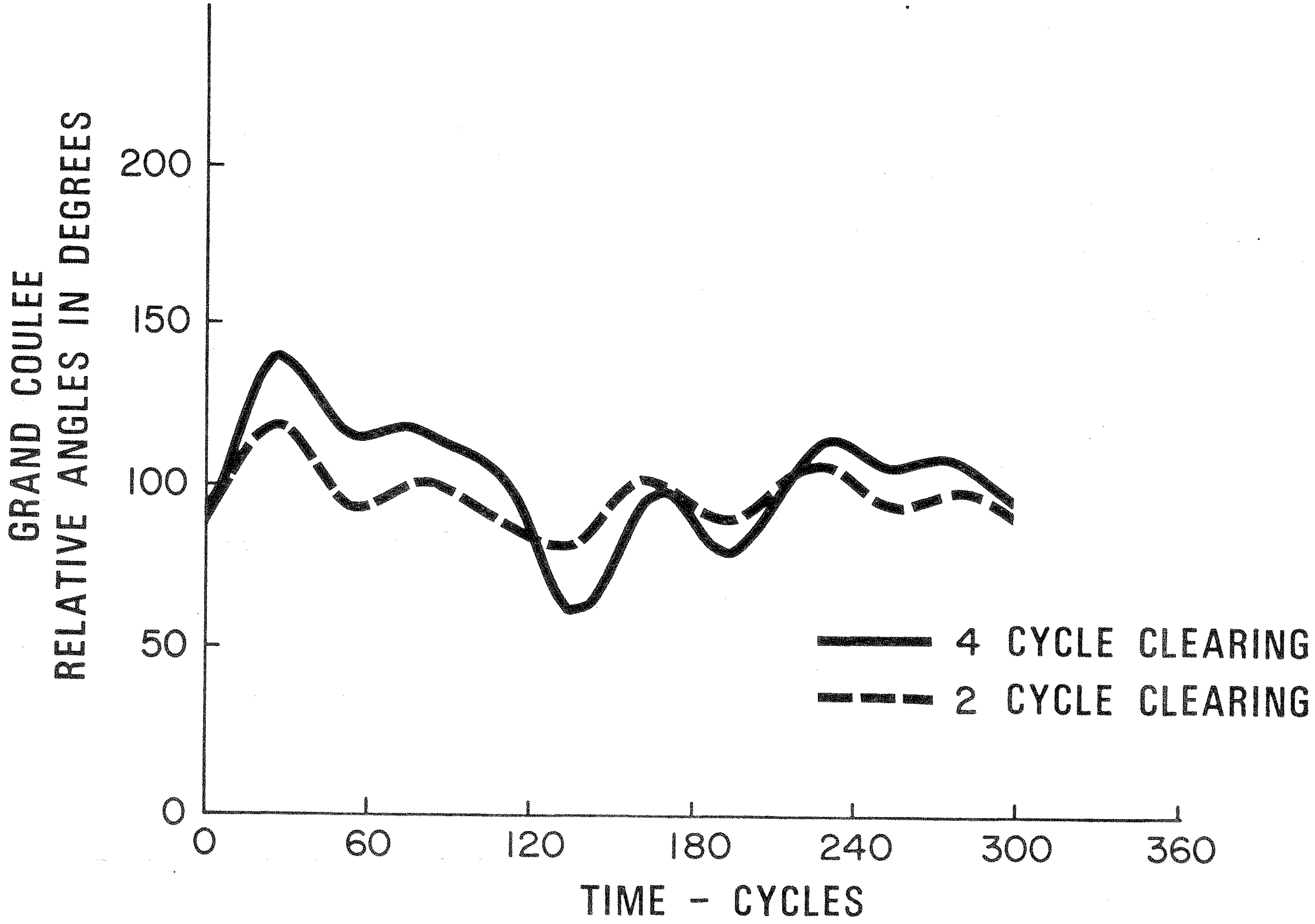
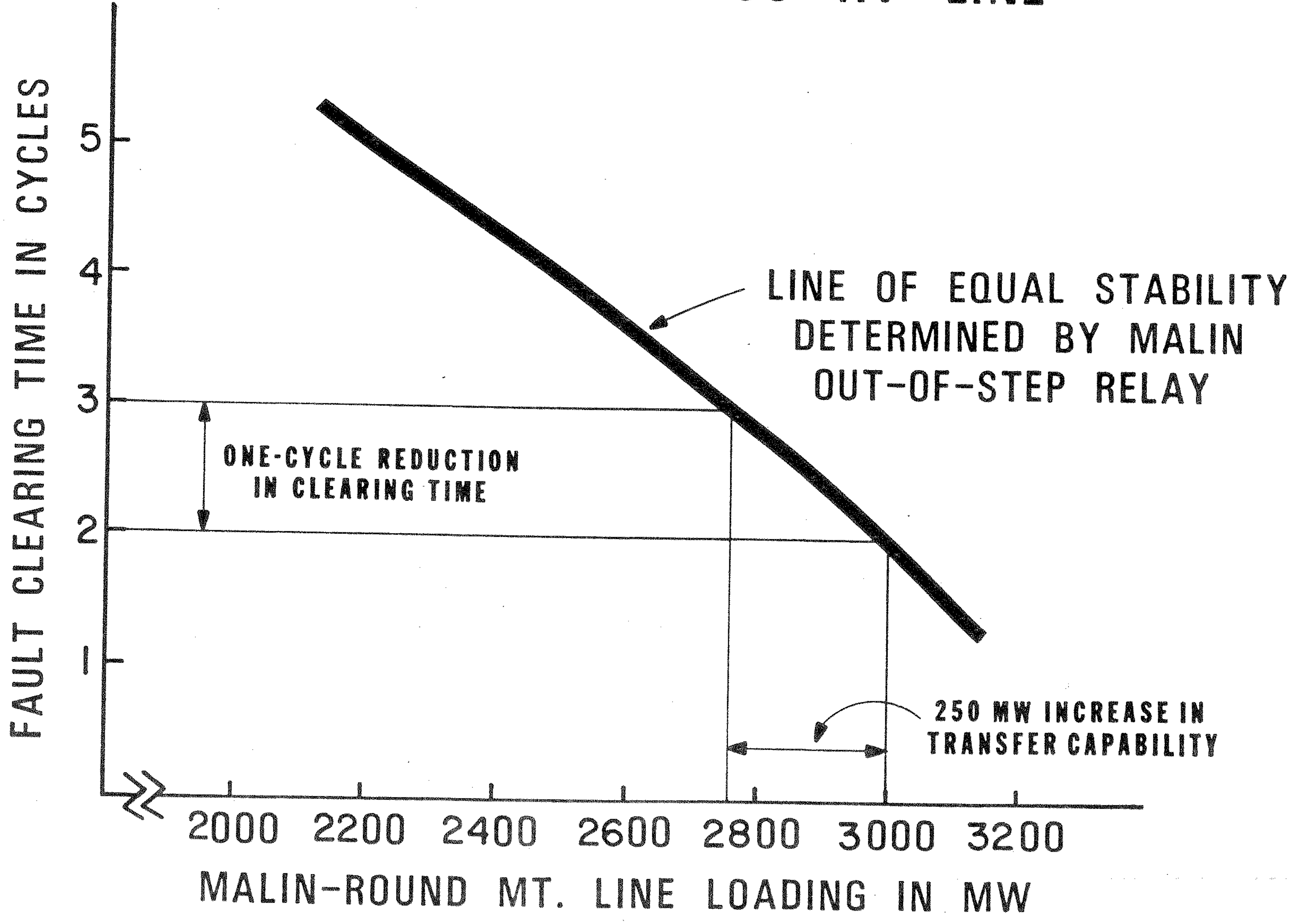


FIGURE 2

3 Ø FAULT AT COULEE
ON THE RAVER 500 KV LINE



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