Analysis of Generator Tripping Incidents on Energizing Nearby Transformers

Pedro Nunes[1], Atef Morched[1] and M. Teresa Correia de Barros[2]

(1) Dept. of Studies and Development, LABELEC, Sacavém (2) Technical University of Lisbon, Lisbon
Portugal

Abstract – **Co-generating units supplying electricity and process steam to a chemical factory, have been put into service relatively recently. The generating units have undergone several costly unwarranted tripping incidents. Tripping incidents were initiated by the generator differential protection and coincided with energizing any of two transformers supplying power to an older part of the plant.**

An investigation was conducted to identify the cause of the mal-operation of the generator's differential protection and to explore means of mitigating the problem. Detailed simulation of system response during the incidents, using the EMTP, resulted in establishing the link between the transformer inrush current phenomenon and the generator differential protection mal-functioning.

The results suggest the use of the second harmonic component of the differential current of the relay to distinguish transformer energization processes from internal generator fault conditions and restrain the relay during transformer energization maneuvers.

Keywords – Transformer Inrush Current, Generator Differential Protection, Modelling of Current Transformers, Saturation Characteristics

I. INTRODUCTION

A gas fired combined cycle co-generating station with two units providing process steam and electricity to a chemical factory has been recently commissioned. The station supplies excess power to the Electricidade de Portugal (EDP) Distribution System in the area, through a weak interconnection link.

The plant generators have undergone several unwarranted tripping causing costly interruptions and restarting processes. These tripping incidents coincided with energizing any of the two power transformers, supplying the older part of the plant, from the high voltage side, at no load.

Tripping of the generators is mostly initiated by the operation of the generators differential protection intended to guard against generator internal faults. Problems emanating from energizing large transformers from limited capacity generators have been experienced at different installations and analysis of the involved phenomena has been reported in literature [1].

II. SYSTEM CONFIGURATION

A simplified single line diagram showing the electrical system of the generating station and the interconnection to the EDP distribution network is shown in Fig.1.

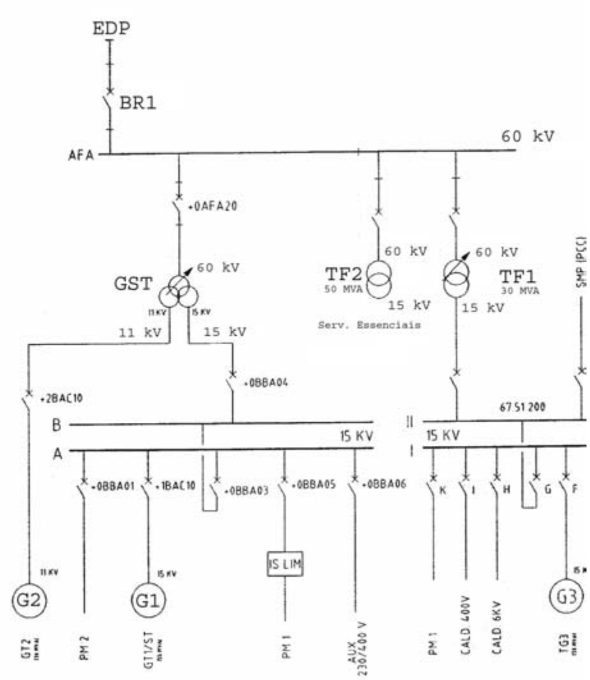

Fig.1 Plant Single Line Diagram

The new part of the plant, shown on the left side of the figure includes the two generators G1 and G2 of capacities 55 and 30 MVA respectively. The generators are connected to the high voltage bus through a three winding step up transformer (GST) 60/15/11kVof rated capacity of 60/40.2/20.1 MVA with natural cooling and 88/59/29.5 MVA with forced cooling. The plant main loads are connected to the 15 kV bus bar where generator G1 is connected. The 60 kV bus is connected to the EDP Distribution network through the breaker BR1.

On the right hand side are the two 60/15 kV transformers TF1 and TF2 of capacities 30 and 50 MVA respectively providing connection to the old 15 kV switch-gear and the connected load and generation. The energization of the TF1 or TF2 transformers from the 60 kV bus while their 15 kV terminals are open circuited results, more often than not, in the tripping of one or both of the generators G1 and G2.

III. GENERATOR PROTECTION

The generators G1 and G2 are equipped with a number of protection systems that disconnect the generators on the occurrence of an internal fault within the generator windings or the development of a system condition that warrants removing the generator from service. Generators G1 and G2 are provided with protection systems including:

- Loss of excitation protection
- Differential protection
- Rotor earth fault protection
- Reverse power protection
- Negative sequence current protection

In most of the reported cases, it was the generator differential protection that initiated generator tripping, as mentioned earlier

Differential protection for generating units G1 and G2 is provided by multi-purpose differential relays. Each relay is fed from two current transformers one at each end of the generator winding with current ratios 2500/1 and 1600/1 for generators G1 and G2.

Each differential relay is provided with a percentage through-current restraint. Therefore it does not operate for a constant differential current, but for an adaptive percentage current related to the through current of the generator. This allows the setting of the operating current of the relay to a low value without risking undesirable operation for external faults. The restraint is zero at through currents smaller or equal to rated current and large at large through currents.

The restrained operating current of the relay can be set at 15,20,25 or 30% of the rated current of 1 A (RMS). The restrained operating current was set to 15% during the reported incidents. As most of the generator differential relays, no harmonic restrain function is provided in this protection system.

IV. Operation of the DifFerential Protection during Transformer Energization

When either of transformers TF1 or TF2 is switched-on from the 60 kV bus bar, high inrush currents flow from the bus to the transformer. Mostly generators G1 and G2 supply these currents, since the connection to the EDP distribution network is a weak connection.

These inrush currents are highly distorted and contain slowly decaying direct current components. They also have high harmonic contents including sizable second harmonic components. These currents are superimposed on the normal generator currents resulting in the distortion of these currents.

Although the total generator currents may not be higher than their rated values, their direct current components can be high enough to drive current transformers into saturation. This is particularly true if current transformers have remnant fluxs from previous current interruptions.

Residual flux in current transformers decay very slowly and current transformers can retain high levels of residual flux for long periods. The currents initiating residual flux in current transformers belonging to the same protection system may have been in opposite directions at the instant of interruption. In addition, the decay of the residual flux in different transformers occurs at different rates. It is, therefore, not uncommon that these transformers retain different levels of residual flux, with different polarities, in their cores for long duration.

The saturation of the current transformers due to the dc component, coupled with the possibility of having different residual flux levels in their cores increases the error in their output currents. These errors can result in high enough differential currents to operate the generator differential relay and trip the generator.

This scenario is especially credible since the operating current was set at a very low value (15%) and the through current, during transformer energization, is not high enough to generate effective restraining action.

V. System Study

A dynamic model is developed using the EMTP, including involved components and their relevant characteristics, to duplicate the system behaviour during the reported incidents. The system modeled is shown in Fig.2. It includes the two generators G1 and G2, the three winding Step-up Transformer GST, the 15 kV bus load and the connection to the EDP Distribution network as well as the energized transformer TF1.

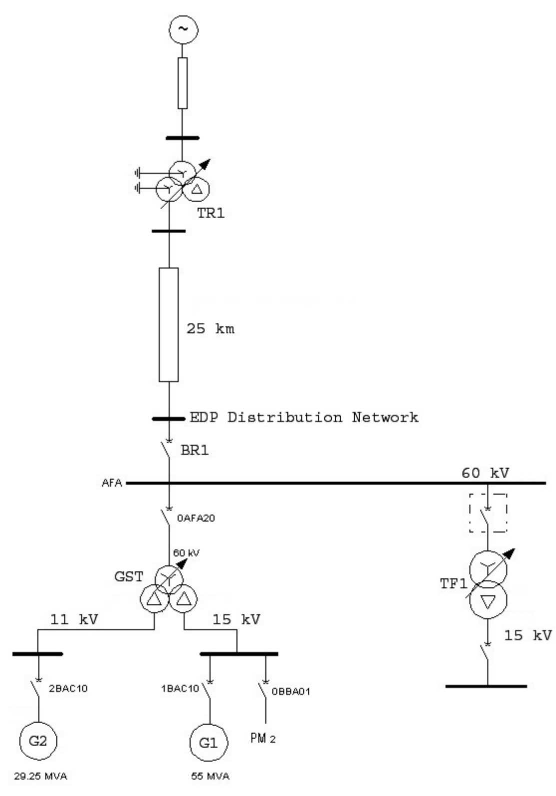

Fig. 2 EMTP Simulated System

In addition to the components shown in Fig. 2, the current transformers connected to the two ends of generator G1 are also modeled including their magnetic characteristics The main parameters of the system components modeled and the modeled features are summarized below.

A. Generators

The two synchronous generator G1 and G2 have the following main parameters.

Generator G1:

- Rated power = 55 MVA
- Rated voltage = 15 kV

Generator G2:

- Rated power = 29,25 MVA
- Rated voltage = 11 kV

The generators are modeled using the Type-59 Synchronous Machine model. The model accounts for the electromechanical and electromagnetic characteristics of generators and reproduces their behaviour under different transient conditions.

B. Power Transformers

Power transformers modeled are: the generator step-up transformer GST, the distribution network step down transformer TR1 and the transformer connecting the 60 kV bus to the old part of the plant, TF1. The nameplate parameters of the modeled transformers are given below.

Transformer GST:

- 3 windings: HV, MV, LV
- Rated voltage: 60/15/11 kV
- Nominal power (ONAN/ONAF): 60/88 MVA; 40.2/59 MVA; 20.1/29.5 MVA
- Rated current: 579.7/850.2 A ; 1547/2271 A; 1059/ 1554 A;
- Connection group: YND11,d11
- H-M short circuit voltage: 17.7% (Base 59 MVA)
- H-L Short-circuit voltage: 12.7% (Base 29.5 MVA)
- M-L Short-circuit voltage: 25.3% (Base 29.5 MVA)

Transformer TF1:

- 2 windings
- Rated voltage: 60/15 kV
- Nominal power: 30 MVA
- Connection group: YNd11
- Short-circuit voltage: 12%

Transformer TR1:

- 3windings
- Rated voltage: 220/60/60 kV
- Nominal power: 63 MVA
- Connection group: YNYN,d11
- Short-circuit voltage: 17%

Transformers are simulated using the BCTRAN model reproducing their magnetization characteristics including saturation and remnant magnetism [2]. The hysteresis loop was modeled using the nonlinear inductance type 96. The hysterysis loop constructed from the information available for the generator step-up transformer and used in the simulation is shown in Fig. 3.

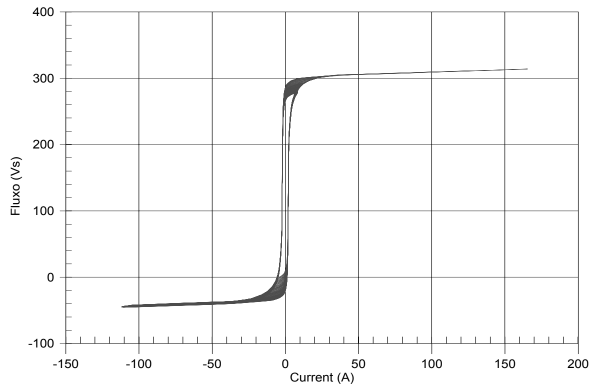

Fig. 3 Hysteresis loop of the step-up transformer (GST)

VI. PROTECTION SYSTEM

The protection system that initiates generator false tripping is the generator differential protection. The operation of the differential protection depends on the differential current as well as the relay characteristics and settings. The differential current is the difference between the input currents to the relay. The relay input currents are the secondary currents of the current transformers feeding the relay. Their values depend on the primary current magnitudes and wave shapes as well as the current transformers remnant flux values and their saturation characteristics.

Therefore, the accurate modeling of current transformers, their magnetization characteristics and saturation conditions is a key element in the assessment of whether the differential protection can mal function under the simulated conditions or not.

A. Current Transformers

Current transformers used for generator G1 are of 2500/1 A ratio and 10 VA burden. Each has three cores: one for measurements with accuracy class .2 and two for protection with accuracy class 5. The measured magnetization characteristics of the of the current transformer protection cores are given in Tables I. Table I shows that the magnetization characteristics of the two cores are not identical.

Current transformers are simulated using the Single-Phase Saturable Transformer Model of the EMTP as shown in Fig.4 [3], where:

Rp – primary winding resistance
Lp – primary winding leakage inductance
Rs – secondary winding resistance
Ls – secondary winding leakage inductance
Tr – ideal transformer

The EMTP Hysteresis Model type 96 is used to represent the magnetic characteristic of the current transformers. The resultant characteristic is shown in Fig. 5.

Table I Magnetizing data of CT1

Secondary 1S1-1S2		Secondary 2S1-2S2	
V	A	V	A
280.6	1	282.4	1
273.1	0.5	275	0.5
266.3	0.2	268.1	0.2
260.3	0.1	262.6	0.1
251.4	0.04	253.7	0.04
244.6	0.02	248.3	0.02
237.8	0.01	239.2	0.01
223.7	0.005	221.6	0.005

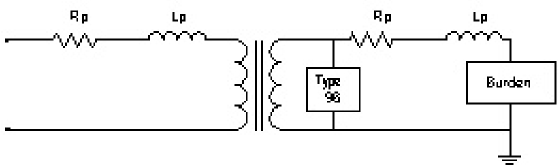

Fig. 4 Current transformer model in EMTP

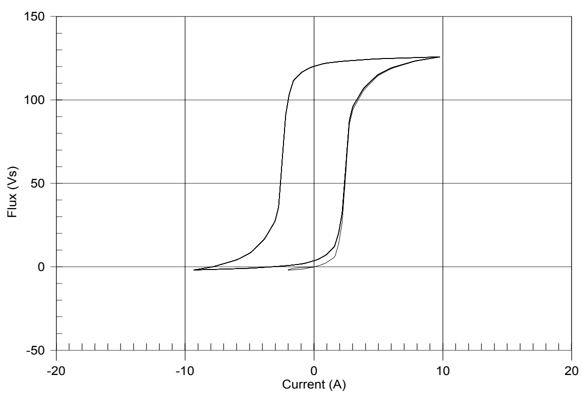

Fig. 5 Current Transformer Magnetization Characteristic.

B. The Differential Relay

The generator differential relay is not modeled explicitly. Its response to the simulated conditions is based on its functional behaviour and its operation settings as given by the relay manufacturer. These are summarized below:

- The minimum restrained operating current is set to 15% of the normal current of 1 A (RMS), resulting in minimum operating current of 0.15 A (RMS).
- The through current restraint function becomes effective only if the through current exceeds the rated current, and increases as the through current increases.
- The operating current, in the absence of the restraining function, is equal to the relay differential current.
- An operating voltage proportional to the operating current is generated within the relay.
- This voltage is passed through a band pass filter to remove the dc component and to eliminate the effects of high frequency transients that may be present in the system.
- The voltage obtained is then rectified and the result of this process is a train of unidirectional voltage pulses.
- The instantaneous values of the voltage pulses are compared with a preset voltage corresponding to the restrained operation setting of the relay (15% of the normal current in this case).
- If the instantaneous value of the voltage of any of these pulses exceeds the operation setting for 4.1 msec. or longer the relay initiates a trip signal.

The secondary currents of the two current transformers connected to the differential protection of generator G1 are monitored during the simulated energization of transformer TF1. These currents are subtracted and the resultant differential current is processed in a similar manner as occurs in the used relay in order to assess the possibility of mal-operation of the relay under the simulated conditions.

VII. Conduction of the Study

Typical operating conditions of the plant were assumed where plant generation, load and exported power were representative of the conditions for which generator tripping occurred. All relevant variables were monitored and analyzed. Detailed description of the simulated conditions is given below.

A. Initial Operating Conditions

A number of operating conditions where the plant is connected to the EDP Distribution Network through the step-up transformer GST and carrying the plant load connected to the 15 kV bus have been tested. Transformer TF1 is initially connected on the 60 kV while its 15 kV side is open circuited. Transformer TF1 was de-energized first to create the proper residual flux level within its core then re-energized to simulate incident conditions.

Simulation results presented in this paper are for the following initial conditions:

- Generator G1 is delivering 30 MW and 24 MVA
- Generator G2 is delivering 21 MW and 19 MVA
- The plant is exporting 10 MW and 11 MVA to the EDP Distribution Network
- The balance power represents the plant load.

B. Simulated Scenario

Transformer TF1 is first de-energized and then re-energized from the 60 kV bus at different instants in time, corresponding to different points on wave of the energizing voltage. The de-energization process creates remnant flux in the transformer core. Closing angles are chosen to produce high inrush currents to simulate especially onerous conditions. Under these conditions the transformer energizing current portrays the distinguishable dc offset and second harmonic content characteristic of transformer inrush currents.

The magnetizing characteristics of other transformers in the system are taken into consideration as well. The resulting energizing currents of TF1 monitored from the 60 kV side is shown in Fig. 6.

The transformer TF1 energizing current is supplied partially by the EDP Distribution Network. However, since the connection to this Network is through a weak link, generators G1 and G2 supply much of the transformer energizing current. The generator G1 three phase currents, during the energization of the transformer TF1 are shown in Fig. 7.

The secondary currents of the current transformers feeding the generator differential protection of G1 are

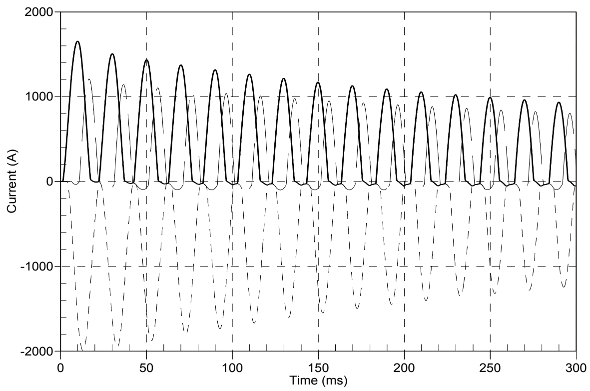

Fig. 6 TF1 Energization Current

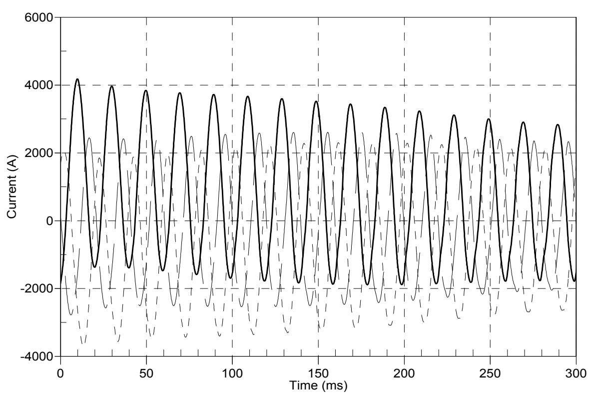

Fig. 7 Generator 1 currents on energizing TF1

monitored. Residual flux levels in the two phase “A” current transformers, due to previous current interruptions, were assumed to be +50% and +65% of the maximum residual flux of the current transformers. The secondary currents of the two current transformers are shown superimposed in Fig. 8.

The differential relay operating current for generator G1 is obtained by subtracting the secondary currents of the two current transformers and is shown in Fig 9 The Fourier analysis of the differential current is shown in Fig.10.

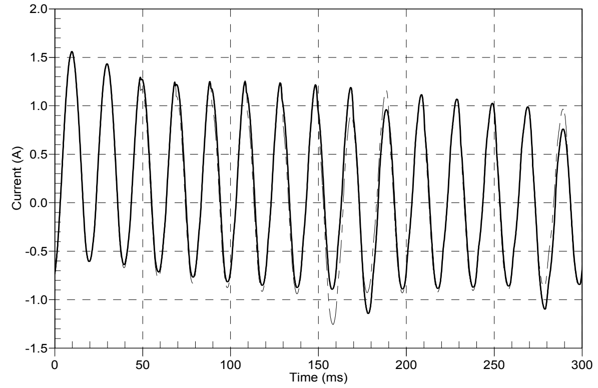

Fig. 8 Current Transformers Secondary Currents of Phase A

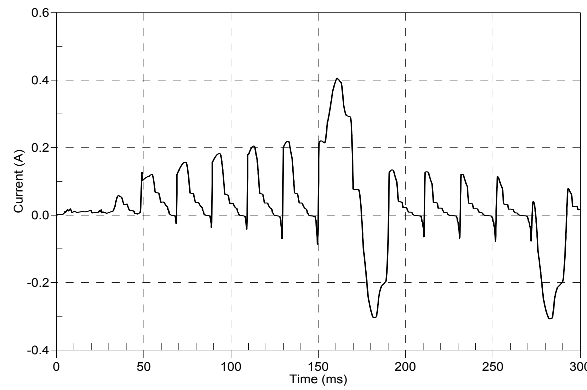

Fig. 9 Differential Current of Phase A

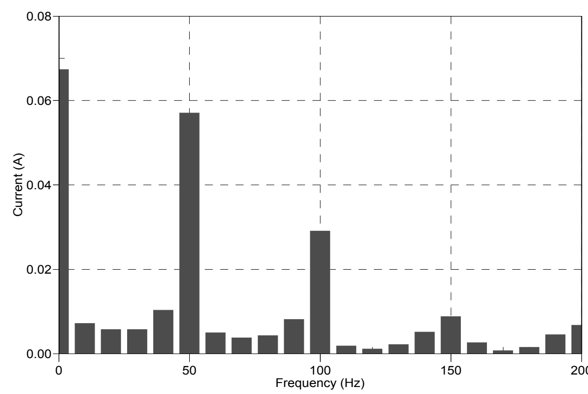

Fig. 10 Harmonic Content of the Differential current

Fig. 10 shows a second harmonic component of amplitude larger than half that of the fundamental in addition to a sizable third and forth components. Therefore, the harmonic components of the differential current can be used to restrain the relay operation under transformer energizing conditions.

The differential current shown in Fig. 9 is passed through a band pass filter to remove the dc and high frequency components. The result of this process is shown in Fig. 11. The filtered differential current is rectified producing a series of unidirectional pulses shown in Fig. 12.

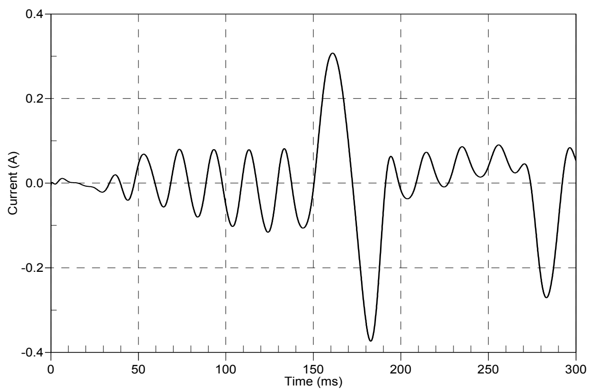

Fig. 11 Filtered Differential Current

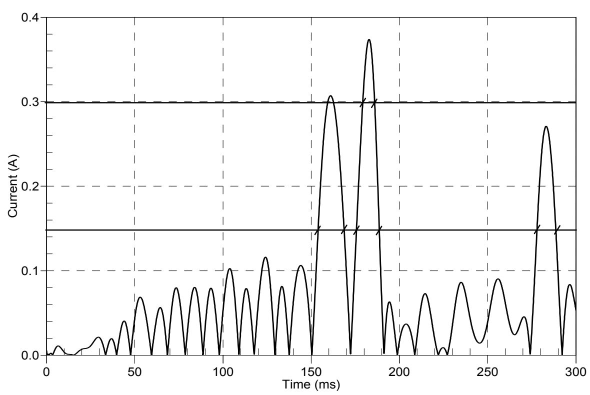

Fig. 12 Filtered and Rectified Differential Current

Examination of the magnitude of the current pulses shown in Fig. 12 reveals that their instantaneous values exceed the operating limit of the relay for longer than 4.1 msec for three of the pulses.

Therefore, it can be concluded that the relay will initiate a generator trip under the assumed conditions. In fact it can be seen from the figure that the differential relay would operate even if its operating current was set at its maximum value of 30% (.3 A).

The residual flux assumed in this case is not excessive, the retained flux is in the same direction in both current transformers and the difference between the residual flux of the two current transformers is only 15%.

Simulation studies were conducted for different residual flux levels and more onerous conditions were identified for situations with residual fluxes, in the two current transformers, of opposite polarity and/or of larger differences in their magnitudes.

VI. CONCLUSIONS

A study was conducted to investigate the incidents of generator tripping coincident with the energization of close by power transformers and the role of the generator differential protection in these incidents.

The analysis was based on detailed simulation of the involved system using the EMTP.

The simulation results demonstrate the cause of the generator differential protection mal-function under transformer energization conditions and its link to the transformer inrush current phenomenon.

The results suggest the use of the second harmonic component of the differential current of the relay to distinguish transformer energization processes from internal fault conditions and restrain the operation of the relay during these maneuvers.

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