POWER QUALITY IN POWER SYSTEMS SUBJECTED TO TRANSIENTS DUE TO SYMMETRICAL AND ASYMMETRICAL FAULTS

CALIDAD DE LA POTENCIA ELÉCTRICA EN LOS SISTEMAS ELÉCTRICOS DE POTENCIA SOMETIDOS A TRANSITORIOS DEBIDOS A FALLAS SIMÉTRICAS Y ASIMÉTRICAS

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Abstract: Electromagnetic phenomena or power quality problems are linked to disturbances that affect power systems. The main objective of this paper is to identify the electromagnetic phenomena that characterize the voltage at a given time and a given location on the power system when a three-phase fault, a single line-to-ground fault, a line-to-line fault, or a double line-to-ground fault occur in a power system. To this aim, a MATLAB program code is developed. This program considers the modeling of power system transient stability responses for simulation purposes. Three models of the synchronous generator are considered. Results obtained in the MATLAB program and commercial software as DIgSILENT PowerFactory have been compared for two power system cases. Simulation results and analysis indicate that short-duration root-mean-square (RMS) variations such as sags, swells, interruptions, and voltage fluctuations are identified as electromagnetic phenomena, and indicate that the three-phase fault is the most severe.

Keywords: Power Quality, power system transients, symmetrical and asymmetrical faults, voltage sags, interruptions.

Resumen: Los fenómenos electromagnéticos y/o los problemas de calidad de la potencia eléctrica están relacionados con las perturbaciones que afectan a los sistemas eléctricos de potencia. El objetivo principal de este artículo es identificar los fenómenos electromagnéticos que caracterizan la tensión en una barra de un sistema de potencia, cuando ocurre una falla trifásica, una falla monofásica, una falla bifásica aislada, o una falla bifásica a tierra. Para ello, se desarrolla una herramienta en MATLAB. Esta herramienta considera el modelado del fenómeno de estabilidad transitoria de un sistema de potencia y tres modelos del generador síncrono. Los resultados se comparan con los obtenidos en el software comercial PowerFactory DIgSILENT para dos casos de sistemas de potencia. En el análisis de resultados se identifican fenómenos electromagnéticos de corta duración (RMS), tales como huecos de tensión, sobretensiones, interrupciones y fluctuaciones de tensión provocados de forma más crítica por la falla trifásica.

Palabras clave: Calidad de la potencia eléctrica, transitorios, fallas simétricas y asimétricas, huecos de tensión, interrupciones.

1. INTRODUCTION

Power quality has become an important issue for electric utilities and customers who expect to have an uninterrupted and reliable supply (Shaik & Reddy, 2016). In this paper, the concept of power quality was taken from IEEE standard 1159-2009 (Institute of Electrical and Electronics Engineers, 2009).

Power system transients are due to a range of causes, the main ones being lightning striking the phase wires in the power system (Tleis, 2019). These causes and disturbances are considered short circuit faults. According to (Tleis, 2019), there are two kinds of typical parallel faults: symmetrical and asymmetrical. The symmetrical is the three-phase fault (TPF) and the asymmetrical is the single line-to-ground fault (SLGF), the line-to-line fault (LLF) and the double line-to-ground fault (DLGF). They were classified according to frequency of occurrence: 3%, 67%, 25%, and 5%, respectively.

When these faults occur in a power system, synchronous generators may lose synchronism and power quality problems may occur. The analysis of the transient stability of power systems involves the computation of their nonlinear dynamic response to those disturbances, but also transient disturbance identification and classification provide information to analyze and take actions that minimize the effects of the power quality problems caused (Jain et al., 2015).

In this way, different commercial software has been developed to simulate and analyze large power systems with different methods for fault diagnosis, analysis of transient stability and analysis of power quality to improve overall safety and reduce financial losses (Cui et al., 2016; Poisson et al., 1998).

Hence, a MATLAB code program has been developed. Trapezoidal rule is selected as the numerical implicit integration method with a simultaneous solution for solving the equations in the MATLAB code program. Programs based on this method are widely used for transient simulation due to the simplicity of this integration rule, as well as to its numerical stability (Aggarwal, 2003; Rodríguez, 2004).

The power system response to symmetrical or asymmetrical faults involves generator rotor angles, power flows, bus voltages, and other system variables. For this paper, transient response is analyzed considering the modeling of the synchronous generator with different forms of excitation control, including manual (constant Efd), automatic voltage regulator (AVR), and AVR and power system stabilizer (PSS). In this sense, the parameter to analyze in the study cases, in terms of power quality, is the phenomena associated with bus voltages.

The study cases (Kundur's test systems) (Kundur, 1993) were simulated in DIgSILENT PowerFactory and MATLAB, specifically a single machine infinite bus power system and a multi-machine power system of 11 buses and 4 synchronous generators.

According to (Institute of Electrical and Electronics Engineers, 2009) and (Comité Europeo de Normalización Electrotécnica, 2015), the power quality transient disturbances of interest to analyze in this paper are the short duration root-mean-square (RMS) variations such as voltage sags, swells, interruptions and voltage fluctuations. The results obtained in PowerFactory and MATLAB were compared.

2. METHODOLOGY

The first part of this methodology is about the modeling of power systems considering the dynamic response of the synchronous generator, and the numerical integration method of the solution used. Moreover, it includes the analysis of faults. All are taken from Kundur (Kundur, 1993).

2.1. Modeling of Power Systems

Considering the nonlinear dynamic response of the power system, the power system model consists of a large set of first-order differential and algebraic equations.
The synchronous machine uses a sixth-order model which represents the dynamics of stator and rotor circuits by two rotor circuits in the direct axis and two in the quadrature axis, as well as the mechanical inertia of the rotor. Moreover, these equations consider the magnetic saturation.

In this paper, three models of the synchronous generator according to alternative forms of excitation control are analyzed. The three models are synchronous machines with: manual excitation control, AVR, and AVR and PSS. Network loads are assumed to be of constant impedance, which is modelled by exponential or polynomial functions.

Transmission lines are modelled as the π model. Power transformers use series impedance, including equivalent resistance and reactance. The overall network/load representation consists of a large sparse nodal admittance matrix equation.

2.2. Analysis of Symmetrical and Asymmetrical Faults

The analysis of symmetrical and asymmetrical faults is necessary to coordinate the protection system of power systems to supply energy continuously with high power quality.

Depending on the asymmetrical type of fault, the equivalent negative- and zero-sequence impedances related to the fault point are computed, combined appropriately, and inserted between the fault point and ground through the method of symmetrical components and Thevenin equivalent for unbalanced systems (Kundur, 1993). This alters the self-admittance of the node representing the fault bus. For the three-phase fault, the single-phase circuit representation of the system is used. This applied fault is isolated from the faulted element by protective relaying.

2.3. Analysis of Transient Power Quality Problems

Transient power quality problems are characterized by a frequency spectrum and a duration (Aggarwal, 2003). According to the table of categories and typical characteristics of power system electromagnetic phenomena from (Institute of Electrical and Electronics Engineers, 2009), for transient analysis, the power quality problems identified are the short duration RMS variations.

Short duration voltage variations are almost always caused by fault conditions, such as symmetrical and asymmetrical short-circuit faults. Depending on the fault location and the system conditions, the fault can cause temporary interruptions; instantaneous, momentary, or temporary voltage dips (sags) or voltage rises (swells); and voltage fluctuations (Heine & Lehtonen, 2003; Institute of Electrical and Electronics Engineers, 2009).

Voltage fluctuations are systematic of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges of 0.95 pu to 1.05 pu specified in (Institute of Electrical and Electronics Engineers, 2009). In Colombia, the current magnitude limits of voltage fluctuations range between effective values of 0.93 pu and 1.05 pu according to (Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), 2013).

2.4. MATLAB program developed

A MATLAB code program for transient stability analysis has been developing at Universidad Industrial de Santander since 2007 (Rodríguez, 2007). The analysis of the effects of power systems exposed to symmetrical and asymmetrical faults has been added. There are different numerical methods for solving the overall power system equations. For this program, the trapezoidal rule was selected as an implicit integration method due to its simplicity and its numerical stability (Rodríguez, 2004). Hence, the state variables and the network variables are solved simultaneously using the trapezoidal rule and the Newton-Raphson method. In this work, this program is used to analyze transient power quality problems.

The algorithm consists of the following steps. First, include the input parameters from the standard of power system model devices and the simulation parameters. At the same time, select the control excitation system for the synchronous generator and the fault event to apply. Second, compute the initial conditions through the Newton-Raphson method to solve the power flow problem with MATPOWER (Zimmerman, 2017). Third, simulate the fault event; after, start with the iterative process to compute the solution of the numerical integration method. Meanwhile, compute the saturation parameters for the synchronous generator dynamic response. Finally, when the iterative process ends, select the desired variable to get the graphical solution. In this work, the variable of interest is the voltage magnitude of the power system buses.

3. SIMULATION AND RESULTS

The purpose of this study was to investigate the behaviour of the MATLAB code comparing its results with the obtained in DIgSILENT PowerFactory software (DIgSILENT GmbH, 2017). Two power system cases were applied in this study.

3.1. Case 1- Single-Machine-Infinite-Bus

The power grid consists of a single machine connected to an infinite bus through a circuit parallel transmission line and a power transformer (Example 13.2) (Kundur, 1993). The input voltage of the generator's excitation system was described in Section 2 (2.1). It was assumed that before the time t=1 s, the network was in steady-state. At time t=1 s, a TPF, an SLGF, an LLF or a DLGF with zero impedance occurred at point F, near the bus 2; in t=1.07 s, with the operation of the protective devices on both sides of the faulty line, the line and fault are cleared.

Fig. 1, 2 and 3 show the results of voltage magnitude of bus 2 for the different control excitation systems and faults applied in MATLAB (blue line) and DIgSILENT PowerFactory (red line). As shown in these figures, the simulation results have a good overlap, so the MATLAB code is nearly accurate. From Fig. 1 when the control excitation system is manual with constant Efd, the system is transiently stable. Fig. 2 shows that with AVR the system is unstable, with oscillatory instability for SLG, LL and DLG faults. Besides, according to Fig. 3, the system with AVR and PSS is stable.

- Manual excitation control

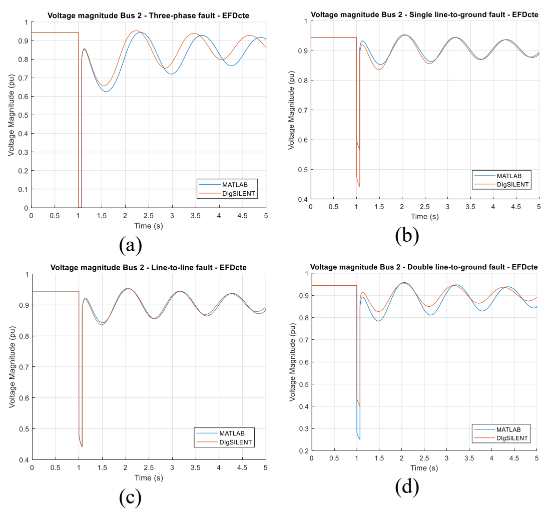
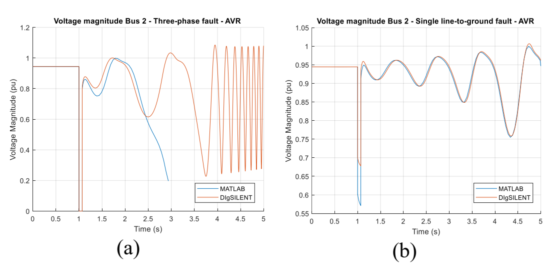


Fig. 1. Voltage magnitude of bus 2 (Case 1) for manual excitation control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

- AVR



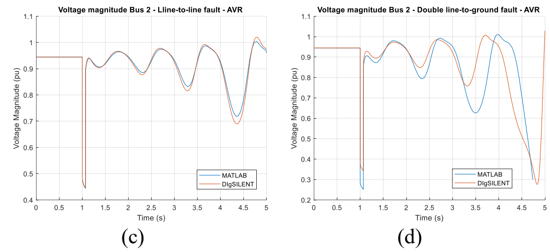


Fig. 2. Voltage magnitude of bus 2 (Case 1) for AVR control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

- AVR and PSS

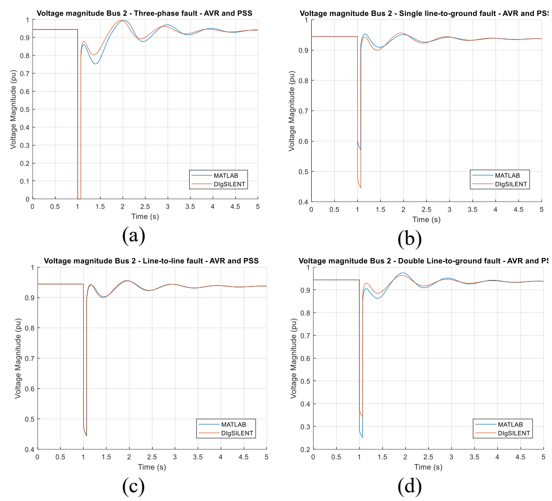


Fig. 3. Voltage magnitude of bus 2 (Case 1) for AVR and PSS control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

To analyze the electromagnetic phenomena of power quality for the 5 s of the simulation results, each value of voltage magnitude of bus 2 was classified according to Section 2 (2.3). After, from the different ranges of values identified in each electromagnetic phenomenon, the critical value was plotted in Fig. 4 considering its time of duration. Hence, the abscissa axis presents 12 study cases that were identified in the simulation results for the combination of control excitation systems and faults applied (1.TPF-constant Efd, 2.TPF-AVR, 3.TPF-AVR and PSS, 4. SLGF-constant Efd, 5. SLGF-AVR, 6. SLGF-AVR and PSS, 7. LLF-constant Efd, 8. LLF-AVR, 9. LLF-AVR and PSS, 10. DLGF-constant Efd, 11. DLGF-AVR, and 12. DLGF-AVR and PSS); the ordinate axis shows the critical value of voltage magnitude of bus 2 in pu, and the axle applicate illustrates the duration of the electromagnetic phenomena identified in seconds.

In Fig. 4, the different colored bars represent the electromagnetic phenomena of power quality identified. Black bars are instantaneous interruptions, red bars are momentaneous sags, magenta bars are instantaneous sags and blue bars are voltage fluctuations. Fig. 4 also presents the voltage limits like the lower voltage fluctuation limit (VF 0.93 pu), the voltage sag lower limit (Sag limit 0.1 pu) and the voltage sag upper limit (Sag limit 0.9 pu). Also, Fig. 4 shows the classification of the study cases according to the type of fault applied such as TPF, SLGF, LLF or a DLGF.

Therefore, Fig. 4 shows that no value exceeds the upper limit of voltage magnitude 1.1 pu, so there are not voltage swells. The voltage magnitude of bus 2 during the fault time of 0.07 s shows in Fig. 4 that, when the TPF was applied there was an interruption, and when the others were applied an instantaneous sag occurred.

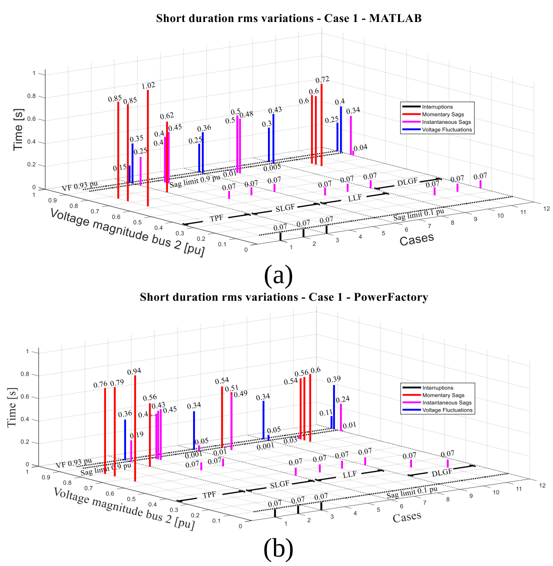


Fig. 4.Short duration RMS variations for the Single-Machine-Infinite-Bus power system identified in MATLAB (a) and PowerFactory (b).

For cases 2, 5, 8 and 11 which refer to the AVR control excitation system with different faults applied, just the first sag was analyzed because the system became unstable before the simulation time. Cases 3, 6, 9 and 12 (which use the AVR and PSS control excitation systems, with different applied faults) found two voltage fluctuations. In cases 1, 4, 7 and 10 (which use the manual control excitation system), the TPF and DLGF faults had one instantaneous sag and three momentary sags, and the SLGF and LLF had six and eight instantaneous sags respectively. Finally, according to Fig. 4, the TPF is the most severe fault followed by DLGF, LLF and SLFG.

3.2. Case 2 – Multi-machine Power System

The multi-machine power system (Example 12.6) (Kundur, 1993) is a Kundur test system which consists of a two-area power system with four synchronous generators, two units for each area, eleven buses, four power transformers, two loads and two shunt capacitors in buses seven and nine.

In Case 2, the different types of faults were applied at t=1 s on circuit 1 from line transmission L7-8 at point F close to bus 8 and were cleared by isolating the faulted circuit simultaneously at both ends in t=1.08 s. The input voltage of the generator’s excitation system was described in Section 2 (2.1).

Fig. 5, 6 and 7 represent the results of the voltage magnitude of bus 7 for the different control excitation systems and faults applied in MATLAB (blue line) and DIgSILENT PowerFactory (red line).

- Manual excitation control

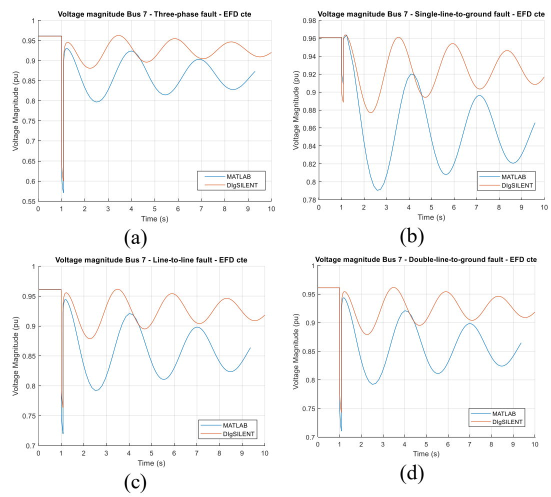
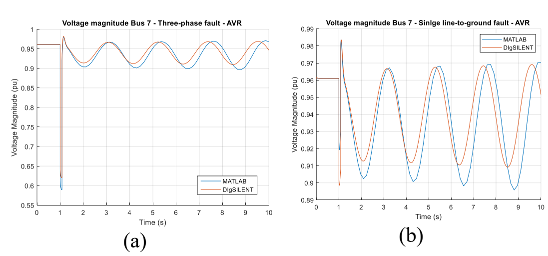
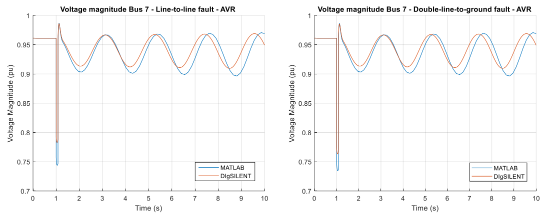


Fig. 5. Voltage magnitude of bus 7 (Case 2) for manual excitation control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

- AVR

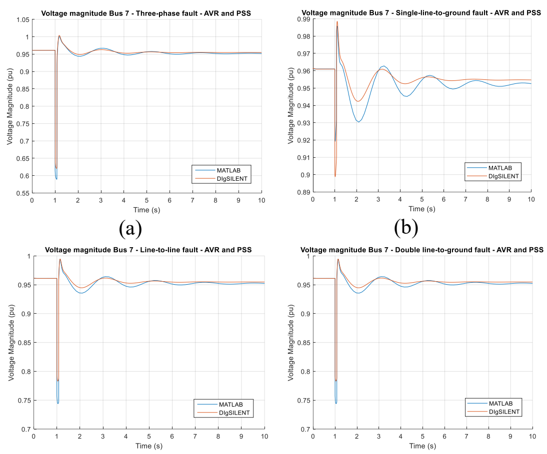




(c) (d)

Fig. 6. Voltage magnitude of bus 7 (Case 2) for AVR control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

- AVR and PSS



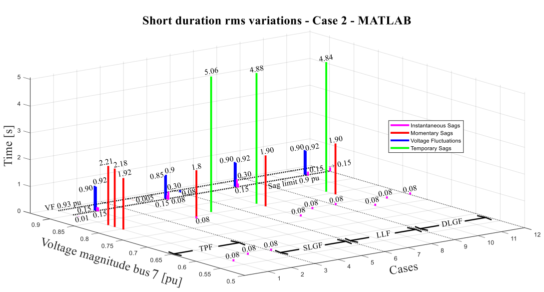
(a) (b)

(c) (d)

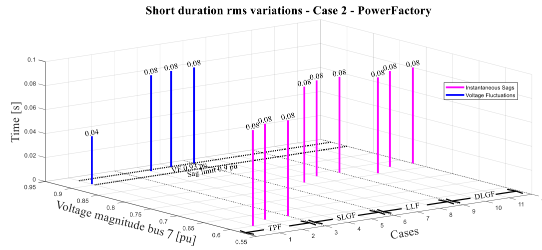
Fig. 7. Voltage magnitude of bus 7 (Case 2) for AVR and PSS control with: (a) TPF, (b) SLGF, (c) LLF and (d) DLGF.

From Fig. 5 when the control excitation system is manual with constant Efd, the system is transiently stable. Fig. 6 shows that with AVR the system is oscillatory unstable. According to Fig. 7, the system with AVR and PSS is stable.

In Fig. 8, the different colored bars represent the electromagnetic phenomena of power quality identified. Green bars are temporary sags, red bars are momentaneous sags, magenta bars are instantaneous sags and blue bars are voltage fluctuations.



(a)



(b)

Fig. 8. Short *duration RMS variations for the Multi-Machine-Infinite-Bus power system identified in MATLAB (a) and PowerFactory (b).*

The voltage magnitude of bus 7 during the fault time of 0.08 s, in Fig. 8, shows an instantaneous sag for each case. The most severe instantaneous sag (magnitude of approximately 0.6 pu) occurred when the power system test is subjected to a TPF with the input voltage of the generator's excitation system controlled manually. Fig. 8 shows that no value exceeds the limit of voltage magnitude 1.1 pu, so there are not voltage swells. Like Fig. 5, 6 and 7, Fig. 8 shows that for study cases with AVR, and AVR and PSS, the MATLAB program has more accuracy. According to the number and severity of the electromagnetic phenomena that were presented in Fig. 8, the TPF is the most severe fault followed by DLGF, LLF and SLFG.

4. CONCLUSIONS

A MATLAB code program was developed to analyze power quality in power systems subjected to transients due to symmetrical and asymmetrical faults. This program was tested by two of Kundur's test systems. This paper presented five power quality electromagnetic phenomena: instantaneous interruptions; instantaneous, momentary, and temporary voltage sags; and voltage fluctuations. According to the number and severity of power quality disturbances, the TPF is the most severe fault followed by DLGF, LLF and SLFG.

As evidenced in Fig. 1 to 3 from the single machine-infinite-bus power system case, MATLAB program and DIgSILENT PowerFactory have high similarity in their results compared to the multi-machine power system case, especially in the manual excitation control form of the synchrono us generators. There are several reasons why this may be so. One reason may be that the numerical integration algorithms that each program uses are different: in the case of the MATLAB program developed, it uses the implicit integration method with the simultaneous solution of the trapezoidal rule, and in the case of DIgSILENT PowerFactory, it uses the partitioned solution with explicit integration of the Runge-Kutta method. However, PowerFactory has the option of simultaneously solving dynamic and system network equations.

Once the simulations were run, the results were not satisfied because it increased the number of swings in the voltage magnitude signal of the power system cases and raised the number of sags and voltage fluctuations. Hence, the difference evidenced in Fig. 7 may be attributed to the Runge-Kutta numerical solution algorithm. The PowerFactory program also computes the rotor angles of the synchronous generators relatively, that is, once it reaches 180 degrees, the following value goes to -180 degrees, while the MATLAB program computes the rotor angles in its absolute form.

For future work, parallel processing could be included in the algorithm of the MATLAB code program to get a faster simulation for larger power systems and analyze power quality disturbances.

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