Impact Analysis of Asymmetric Conditions on an Oil-Filled Distribution Transformer Performance

Análisis del impacto de condiciones de asimetría en el desepeño de un trasnformador de distribución sumergido en líquido aislante.

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ABSTRACT

This paper shows the results obtained from the simulation of a study case about the impact of asymmetric operational conditions on oil-filled distribution transformer useful life. The results depend on the supplied energy level through three different demand profiles (unbalance) mixed with two asymmetric conditions (no asymmetric condition and two additional cases with different asymmetric conditions). The disturbance analysis is realized through the FBD and symmetrical components theories, in order to obtain an equivalent factor to the I_{pu}, which will be used to characterize the transformer loss of life from the temperature rise in the transformer (oil). Finally, it is realized a discussion about the results obtained and the possible analysis field for future studies of this topic (asymmetric conditions).

Key words: Aging factor, demand profile, hot spot, load unbalance, loss of life, phase displacement, thermal-electrical model**.**

RESUMEN

El presente documento muestra los resultados obtenidos a partir de la simulación de un estudio de cado acerca del impacto de las condiciones asimétricas de operación en la vida útil de transformadores de distribución sumergidos en líquido aislante. Los resultados dependen del nivel de energía entregado a través de tres diferentes perfiles de demanda (desbalanceados) combinados con dos condiciones de asimetría (sin condición de asimetrías y dos casos adicionales diferentes de condiciones de asimetría). El análisis de las perturbaciones es realizado a través de las teorías FBD y de componentes simétricas, con el fin de obtener un factor equivalente a I_{pu}, el cual se empleará para caracterizar la pérdida de vida útil acelerada del transformador a partir de los aumentos de temperatura en él. Finalmente, se realiza una discusión acerca de los resultados obtenidos y del los posibles campos de análisis para futuros estudios realizados en este tema (condiciones operacionales de asimetría).

Palabras clave: Desbalance de carga, desplazamiento de fase, factor de envejecimiento, modelo termoeléctrico, pérdida de vida, perfil de demanda.

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INTRODUCTION

The current loads used from the users produce many harmful effects on the transformer operation, due to the non-linear loads connected to the distribution system. As part of the distribution system, the transformers receives all the disturbances from the user loads, which damages the transformer insulation (paper and insulating oil). The insulation degradation generates an accelerated loss of life on the transformer, affecting the distribution system performance due to more frequently changing of the system elements, i.e., a higher monetary inversion.

Furthermore, a significant part of the current studies are focused on waveform distortion (harmonic), setting aside the asymmetric condition analysis, which promotes the analysis method development for the asymmetric conditions on distribution transformers (<300 kVA), from the current elements to analyze the transformer loss of life.

1. MODELLING OF UNBALANCE EFFECT ON OIL-FILLED DISTRIBUTION TRANSFORMERS.

The characterization of the damage level of the oil-filled transformer insulation due to the asymmetric conditions is carried out through a thermal-electrical evaluation model, which permits an analysis of the degradation level of the insulations and the transformer useful life.

The electrical model for a transformer operating under asymmetric conditions is based on the power losses presented during its operation, i.e., the effects generated such us a low power factor (phase displacement) or an over fluxing in the core (unbalance).

Those effects are characterized through a power separating method, which permits to analyze the disturbances effects (non-active power) independently from the normal transformer operation (active power) using the FBD theory 0, in

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order to obtain a factor that permits the active and non-active effects grouping.

Once the effects on the transformer are characterized by their grouping, the obtained factor permits to characterize the temperature variations and the transformer thermal characteristics due to the asymmetric conditions by the implementation of a loss of life model. The estimation realized with this model is carried out from the Arrhenius equation, which is an accepted quantification method of transformer loss of life related to temperature changes.

1.1. Electrical modelling.

For an operational asymmetric condition on the transformer, the electrical performance is evaluated through the next steps 0:

- The transformer power losses are determined under the operational asymmetric conditions.
- Active (non-disturbance and symmetric) and non-active power is described, in order to organize the power losses.

The common used model for the transformer analysis (pi-model) is not very useful in order to evaluate the performance of a three-leg transformer under asymmetric conditions; because of this, it must be involved a model that permits to include each phase current contribution to the core net flux (figure 1).

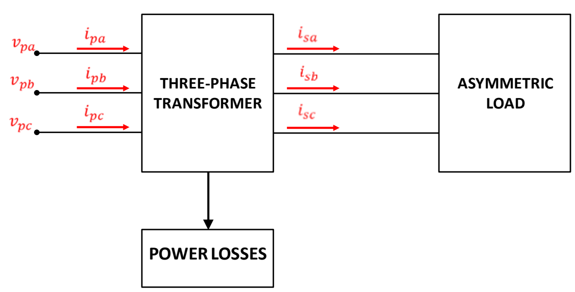

Fig. 1 Model used to describe the core net flux. (*Source: The authors)*

This model lets to analyze the magnetic flux of a one-core three-leg transformer, in which the primary and secondary windings (per phase) are in the same leg; it permits that the magnetic flux be distributed as it is shown in the figure 2.

This transformer distribution allows the magnetic flux analysis depending on the hysteresis cycle (non-saturation considered for this exercise, transformer lineal performance); the magnetic flux on figure 2 is be modelled through a magnetic circuit, as shown in figure 3.

From the magnetic circuit is obtained the expression: (1)

$$\Im_k = N_p i_{pek} + N_s i_{sk}, k = a,b,c \quad (1)$$

Where:

$\Re_k$: Reluctance for each transformer leg ($k = a,b,c$).

$\Re_0$: Dispersion reluctance.

$\Im_k$: Magnetomotive Force (fmm).

N_p , N_s : *Primary and secondary winding turns.*

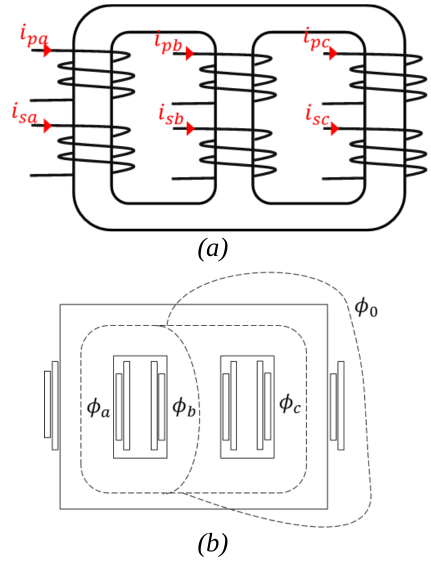

Fig. 2 Electromagnetic element distribution on the three-leg transformer: (a) currents distribution; (b) magnetic flux. (*Source: The authors)*

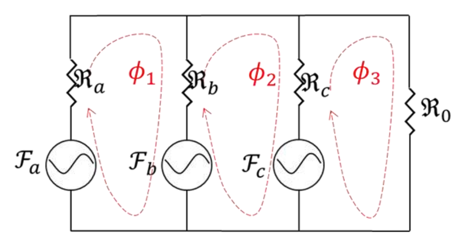

Fig. 3 Transformer magnetic circuit. (*Source: The authors)*

Once the unbalance magnetic effect on transformer is determined, the asymmetric effect magnitude on the transformer must be characterized. It is realized through the transformer active and non-active power delivered by the transformer, applying to the FBD theory.

This theory permits a power analysis by means of a current decomposition for poly-phase systems, i.e., a current separation between active and non-active currents as is shown in (2):

$$I_e^2 = I_a^2 + I_x^2 \; ; \quad I_x^2 = I_{au}^2 + I_{Qu}^2 + I_{Qd}^2 + I_h^2 \quad (2)$$

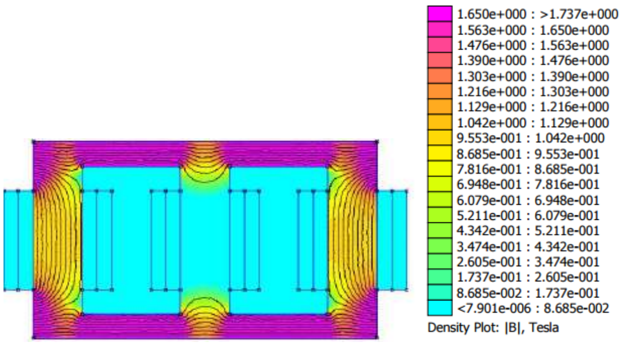

Fig. 4. Example of magnetic flux distribution for an unbalance condition. (*Source: The authors*)

Where I is the transformer current, I_e is the effective current, I_a is the active current (active consumed power), I_x is the non-active current, I_{au} is the active unbalance current, I_{Qu} is the reactive unbalance current, I_{Qd} is the reactive displaced current and I_h is the harmonic current.

For this case, the harmonics effects are despised, then this topic is already analysed in other papers. With this current decomposition, it is possible to describe the asymmetric grouped effects, in order to obtain a factor called "$\tilde{I}_{pu}$" (per unit current), which will permit the transformer thermal behaviour for its loss of life, through the expression (3):

$$\tilde{I}_{pu} = \sqrt{I_a^2 + I_x^2} = \sqrt{I_a^2\left(1 + \frac{I_x^2}{I_a^2}\right)} \quad (3)$$

Once the asymmetric condition is characterized, the transformer unbalance condition must be determined by means of its derating. According to other papers, the transformer derating consists in five steps:

<u>*Step 1*</u>: Transformer load losses calculation under balance and sinusoidal condition:

$$P_T = P_{NL} + P_{LL} \;;\; P_{LL} = P_{I^2R} + P_{EC} + P_{OSL} \quad (4)$$

<u>*Step 2*</u>: Addition of an unbalanced condition (load or voltage), maintaining the fundamental load currant and output voltage at rated values:

$$I_S^{\,1} = V_S^{\,1} = 1pu \quad (5)$$

Step 3: If the output voltage is modified by a reactive power demand, compensate it by adjusting the fundamental input voltage.

Step 4: Re-calculate the total power losses under asymmetric conditions to determine the additional losses:

$$\Delta Losses\% = \frac{P_{Loss-new} - P_{Loss-rated}}{P_{Loss-rated}} \times 100\% \quad (6)$$

Step 5: Using a simulation support software, decrease the load magnitude to equal the total losses and the rated losses, using an randomly valued resistance in series with the load, to adjust its value:

$$P_{loss}\Big|_{I_S^{\,1} = I_{derrated}} = P_{Loss,rated} \quad (7)$$

Step 6: The derated apparent power is calculated as:

$$kVA_{derated} = kVA_{rated} \times I_{derated} \quad (8)$$

$$Derating = (1 - I_{derated}) \times 100\% \quad (9)$$

Nevertheless, it is important to describe the asymmetric load effects with a more recognized method, i.e., the "symmetrical components". The applying of the symmetrical ingredients permits to determine an asymmetric level in voltage or current of three-phase systems.

First, must be calculated the symmetrical components from the three-phase quantities, as the Fontescue theorem is shown in (10):

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (10)$$

Once the symmetrical components are defined, must be defined the voltage and current unbalance factor (VUF and CUF), as follows:

$$VUF = \frac{V_2}{V_1} = \sqrt{\frac{1 - \sqrt{(3 - 6\beta)}}{1 + \sqrt{(3 - 6\beta)}}} \quad (11)$$

$$\beta = \frac{V_{ab}^{\;4} + V_{bc}^{\;4} + V_{ca}^{\;4}}{(V_{ab}^{\;4} + V_{bc}^{\;4} + V_{ca}^{\;4})^2} \quad (12)$$

Where V_{ab}, V_{bc} and V_{ca} are the rms values of fundamental frequency voltage fasors of the three-phase system, Z_1 and Z_2 are the positive and negative impedance components of the transformer. The Factors CUF and VUF permit to describe the unbalance level for the transformer current and voltage.

1.2. Thermal modelling

Once the factor $\tilde{I}_{pu}$ is obtained, can be determined the heat transference on the oil-filled distribution transformer due to grouping effect of the asymmetric condition, the power losses and the load. The very complex interaction of the transformer with its natural and electrical environment (heat flux through the transformer oil to and from the environment) is known, generating a thermal-dynamical interaction between them (transformer and environment).

The current thermal model proposed in the IEEE C57.91 evaluates two important temperatures for the useful life-aging factor of the transformer: the hot spot (Θ_H) and the top

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oil (Θ_{Oil}) temperatures, through a triple interaction with the ambient temperature (Θ_A).

The top oil temperature variation due to its interaction with the ambient temperature is calculated as described in (13):

$$\frac{I_{pu}^{\sim\,2}\beta+1}{\beta+1}\left[\Delta\Theta_{Oil-R}\right]^{\frac{1}{n}}=\tau_{Oil}\frac{d\Theta_{Oil}}{dt}\left[\Theta_{Oil}-\Theta_A\right]^{\frac{1}{n}} \quad (13)$$

Where: $I_{pu}^{\sim}$ is the load current per unit; β is the ratio of load to no-load losses; τ_{oil} is the top oil time constant in min; $\Delta\Theta_{oil-R}$ is the rated top oil rise over ambient in °C; *n* is the exponent who depends of the cooling method (empiric) IEEE C57.91.

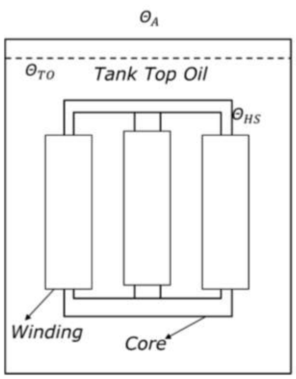

Fig. 5 Transformer thermal interaction. (*Source: The authors*)

Once the top oil temperature rise is determined, the hot-spot temperature is calculated through (14):

$$\frac{I_{pu}^{\sim\,2}\left[1+P_{EC-Rated(pu)}\right]}{1+P_{EC-Rated(pu)}}\left[\Delta\Theta_{H-R}\right]^{\frac{1}{m}} = \tau_H\frac{d\Theta_H}{dt}\left[\Theta_H-\Theta_{Oil}\right]^{\frac{1}{m}} \quad (14)$$

Where: $I_{pu}^{\sim}$ is the load current per unit; Θ_H is the hot-spot temperature in °C; τ_{oil} is the top oil time constant in min; $\Delta\Theta_{H-R}$ is the rated hot spot rise over ambient in °C; *m* is the Empirical exponent (depending on the cooling method).

Once both temperature models (hot-spot and top oil) are determined, the transformer thermal model is complete. The final model graphic is displayed on fig.
The implementation of (14) and (15) determines the transformer aging acceleration through the transformer hottest spot behavior. The transformer aging factor is characterized resorting to the Arrhenius equation 0, applied to the oil-filled transformers aging.

Once the transformer hottest spot temperature is characterized, the aging factor for the transformer is at first obtained from the modified Arrhenius equation in (15), as described in IEEE C57.91:

$$F_{AA}=e^{\left[\frac{B}{383}-\frac{B}{\theta_H+273}\right]} \quad (15)$$

Where *B* is a constant depending on the reference temperature. In this case, the reference temperature is 110 °C, so from IEEE C57.91, so the constant value is *B = 15000*. Finally, the Per Unit loss of life (L_F) of the transformer is obtained according to (16):

$$L_F=\frac{\int F_{AA}dt}{\int dt} \quad (16)$$

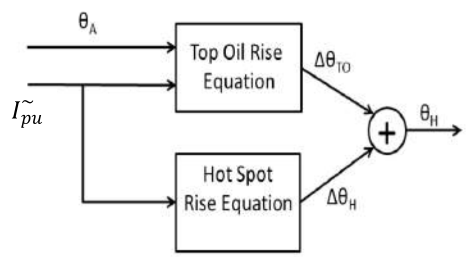

Fig. 6 Transformer mathematical thermal model. (*Source: The authors)*

2. STUDY CASES

As study cases were developed three asymmetric conditions: the first refers to a symmetric condition (non-unbalance, non-phase displacement); the second refers to an unbalanced current case without phase displacement; the third case refers to an asymmetric current condition (unbalanced load and phase displacement). The transformer conditions and characteristics are shown in table I; the load values used on the three cases to generate the asymmetric conditions are shown in table II.

Table I. Transformer Description (*Source: IEEE C57.91)*

Characteristic	Magnitude / Characteristic
Rated Power (kVA)	75
Voltage (V)	11400/214
Connection group	Δ-Y
DC Resistance (primary winding, Ω)	2,023
DC Resistance (secundary winding, Ω)	0,0083
No load losses (P_{NL}, VA)	687,7
Rated total stray losses ($P_{TSL-Rated}$, kVA)	1,43
Rated top oil rise over ambient ($\Delta\theta_{TO}$, °C)	38,3
Rated hot spot rise over top oil ($\Delta\theta_H$, °C)	22
Ambient temperature (θ_A, °C)	25
Reference hottest spot temperature (°C)	110
Ratio of load loss (rated) to no load loss	5,48
Top oil time constant (hrs)	3,5
Hot spot time constant (hrs)	0,167
Exponent *m*	0,8
Exponent *n*	0,8
Expected useful life (years)	22,5

The analyzed cases do not consider the core saturation, whose impact is expected to accelerate the transformer degradation due to the addition of harmonics effect, which have been already evaluated.

The oil-filled transformer and its characteristics are ideally determined using Standards values, i.e., the transformers values were taking from 0. The evaluated transformer is an ONAN transformer type (Oil Natural Air Natural), so the empirically determined constants *m* and *n* are taken from the IEEE Standard **¡Error! No se encuentra el origen de la referencia.**.

Table II. Used load description for each case *(Source: The authors)*

	Resistance [Ohm]	Current [pu]	Angle [Grade]
Case 1			
Phase A	1+j0	0.97	-1
Phase B	1+j0	0.97	-121
Phase C	1+j0	0.97	119
Case 2			
Phase A	0.81+j0	1.21	-1.21
Phase B	1.02+j0	0.97	-121
Phase C	1.23+j0	0.8129	119.16
Caso 3			
Phase A	0.81+j0	1.36	72.95
Phase B	0.72+j0.81	1.17	-149.93
Phase C	0.76+j0.82	0.88	-1.4

Table IV. Symmetrical components values for each case. *(Source: The authors)*

	$\%i_0$	$\%i_2$	Ix/Ia (%)
Caso 1	0	0	0
Caso 2	11.67	11.62	26.19
Caso 3	20.64	35.12	69.3

The first case indicates a reference case in which the transformer load is about the 100% of its rated power, being this case near to the real charge of a distribution transformer, although the power quality disturbance level is ideal (in operation, there is more effect with larger magnitude and impact on transformer performance).

The second and the third case refer cases in which there is an asymmetrical condition around the transformer nominal current (1pu): the second case only includes load unbalance ant the third case includes load unbalance and phase displacement. In the table III are shown the obtained values for the effective, active and non active currents (including its components) in each case.

Once were obtained the current orthogonal components for each case, were calculated the symmetrical components from the values of the table II and the asymmetric characterization from (3), being shown these results in the table 4.

Table III. Obtained values for each component on the orthogonal decomposition. *(Source: The authors)*

	Case I	Case II	Case III
I_e	245.23	209.09	245.23
I_a	245.23	202.27	201.47
I_x	0	52.98	139.82
I_{au}	0	40.10	70.22
I_{Qd}	0	0.58	77.85
I_{Qu}	0	33.99	133.54

In the figure 7 are shown the final loss of life results for a 20.55 years time evaluation, which is recommended from the IEEE C57.91. It is shown that the most reference case (case 1) is the least harmful scenario for the transformer (less loss of life). It is so due to the non-presence of PQ disturbances.

The results for the case 2 indicates that the selected unbalance value between the phases generate a considerable loss of life, due to the presence of this PQ disturbance, which is generated from the occurrence of a displacement due to the unbalanced magnetic flux in the core (depreciation of harmonic effects).

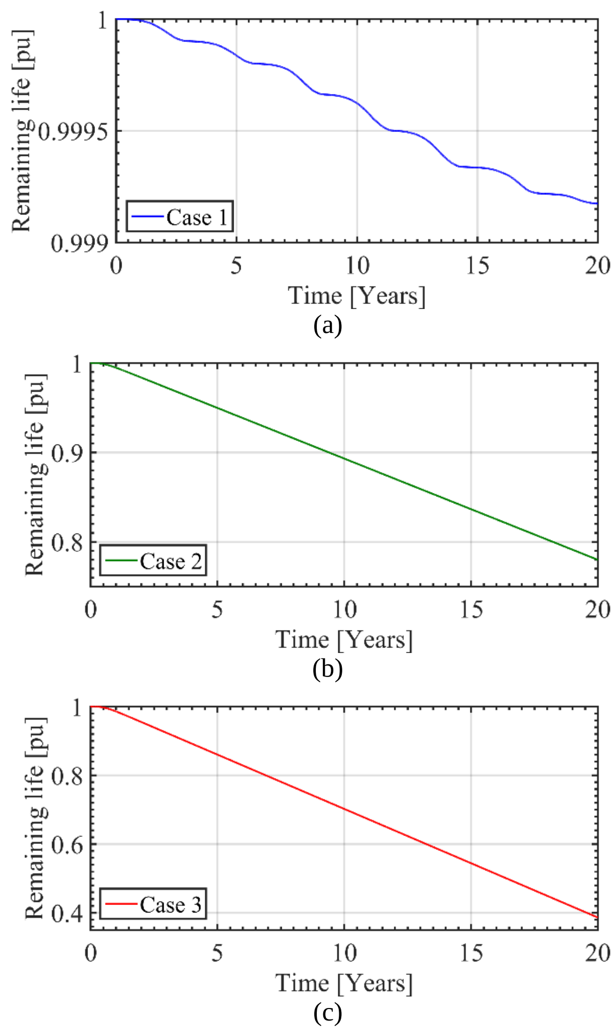

Fig. 7. Obtained loss of life for each case: (a) Case 1; (b) case 2; (c) case 3. (Source: The authors)

As the case 3 included unbalance and phase displacement, it results on the most detrimental case for the transformer loss of life. The conjoined effects of load unbalance and phase displacement generates the largest loss of life for the transformer, due to the added effects of the PQ disturbances and the rated power in transformer (hot spot temperature rise).

The remaining life limits for table V are characterized by three zones: three green zone is for the remaining life values between 0,95 to 1 pu; the yellow zone is for the remaining life between 0,70 to 0,95 pu; and the red zone is for the remaining life between 0 to 0,70 pu.

Table V. Remaining life for each asymmetric case.

	Year 5	Year 10	Year 15	Year 20
Case 1	0.9998	0.9996	0.9993	0.9992
Case 2	0.9498	0.8931	0.8365	0.7798
Case 3	0.8602	0.7022	0.5442	0.3863

3. DISCUSSION

As it was shown, the asymmetric condition effects generate a low impact on the transformer loss of life, due to the low provision to the increase of the total delivered power by the transformer, i.e., in relation with the load charge magnitude.

It provides a new question about the transformer operation under these conditions: ¿what will be the impact on transformer loss of life, when the asymmetric condition implicates an overloading on the transformer?

It is important to be the next step on the asymmetric conditions on distributions transformers operation, because the core saturation characterized from the hysteresis cycle was not contemplated in this paper.

Additionally, a load that exceeds the transformer rated power allows a rising on the hot spot temperature, accelerating the transformer loss of life, being this effect (core saturation and hot-spot temperature) an interesting, harmful and more realistic state for the distribution transformers with rated power under 300 kVA.

4. CONCLUSIONS

Although the use of non-linear charges is extended, the effect that they generate on the distribution system due to unbalanced load and phase displacement is not so larger as the generated by the harmonics.

Even though the unbalance load and the phase displacement generates a higher acceleration on transformer loss of life, the impact of unbalance on transformer loss of life is larger than the impact of phase displacement.

The impact of PQ disturbances on the loss of life acceleration for oil-filled transformers depends on the load magnitude, i.e., the larger load the larger PQ disturbance effects.

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