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# APPLICATION OF THE RELATIVE POWER CONTRIBUTION METHODOLOGY TO THE ANALYSIS OF A CONTROL SYSTEM FAILURE

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## ABSTRACT

The Relative Power Contribution methodology has been applied to delineate the initiating event leading to a BWR transient. Diverse reactor signals were analyzed to calculate the coefficients required on the relative power contribution method. Those coefficients were computed from an autoregressive multivariable model. Among the signals used in the analysis of the transient event are total flow through the core, pressure drop across the core, feedwater flow, and reactor power. Analyses of the same type of transient event showed a resonance of the main event frequency on the range within which it has been considered and observed frequencies related to some failures of certain control systems of a nuclear power plant. Those analyses employed the short-time Fourier transform or the power spectral density, for time-frequency and frequency-only domains, respectively. In this work, the same value of the frequency of the resonance mentioned above was obtained through the relative power contribution analysis, but, furthermore it was found that the feedwater flow behavior had an important impact on the transient event, and also that the transient event was not initiated by a reactivity-related instability.

## INTRODUCTION

Most instabilities occurring on forced-convection Boiling Water Reactors (BWRs) with external recirculation loops can be divided into three main categories [1]: those due to failure of diverse plant controllers; other instabilities have as primary cause feedback reactivity mechanisms; and those due to thermalhydraulic issues in the core. All these three instability types can eventually lead to power oscillations, and thus they could in some circumstances present a hazard to fuel integrity. Also, different instabilities have each different time periods during a power oscillation. Therefore, analysis techniques that can provide information about the time scales occurring during events leading to different types of instabilities are useful to determine the extent to which fuel damage could happen.

One key parameter to consider during power oscillation is the capability of the components of the fuel pin to transport

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the heat generated in the pellet to the coolant. The time range for heat transfer can be referred as to a thermal time constant of the fuel element. Such a time period clearly depends on the specific design (material and geometry) of the fuel pin and assembly. In the case that this fuel time constant is less than the period range of the power oscillation, the clad will experience a number of thermal and mechanical stresses due to the increase-decrease temperature changes. Of the instability types mentioned, the first one has been observed to exhibit periods of about 20 seconds per full oscillation. Such a period is about three times the thermal time constant postulated for many types of fuel assembly designs in BWRs, and thus transient events originated by failure of different controllers are particularly important for analysis in both time and frequency domains.

While post-event analysis in time domain can offer most of the relevant results required for operation and licensing issues, frequency domain information can delineate feedback mechanisms involved in the event, so important data can be input to system codes simulating the transient and thus making possible a deeper analysis of the transient and consequences. Moreover, quick analyses in frequency domain for obtaining information on the original cause leading to the instability are directly possible from the different equipment and component signals.

In this work, it is analyzed an event where a pressure regulator of an electrohydraulic controller failed. As mentioned before, this type of events can lead to instabilities. Analyses using the short-time Fourier transform [2] and the power spectral density [3] techniques, provided information of the event in the time-frequency and frequency-only domains, respectively. Both techniques showed a peak on the power spectrum at the 0.055 Hz, which corresponds to a resonance of the main power oscillation frequency. Thus, this frequency was taken as the value to which the relative power contribution method was applied so the origin of the perturbation could be determined.

## ACRONYMS

| | |
|---|---|
| BWR | Boiling Water Reactor |
| DPC | Pressure Drop across the Core |
| DPP | Pressure Drop of Recirculation Pump |
| FFW | Feedwater Flow |
| JPF | Jet Pumps Flow |
| MAR | Multivariate Autoregressive Model |
| PDC | Pressure Drop in the Core |
| POW | Power of the reactor |
| PRP | Power Recirculation Pump |
| RFW | Flow Recirculation Pump |
| RPC | Relative Power Contribution |
| TFC | Total Flow across the Core |

## NOMENCLATURE

| | |
|---|---|
| $A(k)$ | autoregressive coefficients |
| $f$ | frequency |
| $P_{ii}$ | power spectrum |
| $P_{ij}$ | cross spectral density |
| $\varepsilon_t$ | driven noise |
| $x_i$ | noise signals |
| $\sigma_j$ | covariance |
| $R_{j\to i}$ | relative power contribution |

## THE RELATIVE POWER CONTRIBUTION (RPC) METHODOLOGY

Peaks and valleys shown on power spectra are related to the dynamics of the system under study and from which signals could be obtained. In this work, the system under study is a BWR, including its control systems actuation. For each peak or valley's specific frequency value in the spectrogram of a variable of interest, it is possible to determine the influence of other different variables involved in the process upon the reference variable of interest, by applying the RPC method [4]. The relative power contribution analysis is a technique used to evaluate controls with feedback from diverse systems or processes. It is based on the Multivariate Auto-Regressive (MAR) modeling. The RPC values are computed from the autoregressive (AR) coefficients resulting from a MAR model. The relative power contribution methodology has been presented in detail in several references, as for example [5] and [6].

For completeness, the RPC methodology is briefly introduced next. First, the MAR modeling is defined by

$$Z_t = \sum_{k=1}^{p} A(k) Z_{t-k} + \varepsilon_t \tag{1}$$

where $\varepsilon_t$ is a white noise process with zero mean and variance $C_\varepsilon$. The $d \times 1$ vector $Z_t = (z_{1,t},\dots,z_{d,t})'$ contains the ensemble of the $d$ time series (already with zero mean) of the different signals involved in the analysis, and $p$ is the order of each AR model. The symbol ´ implies the transposed operator. The MAR modeling requires that the value of each series depends only on previous values in the series and the white noise $\varepsilon_t$, as shown on (1). The dependence is considered as a linear combination of the values in the series. The parametric spectrum of the MAR model can be calculated from the AR coefficients $A(k), (k = 1,\dots,p)$ and the covariance matrix $C_\varepsilon$, as follows

$$P_z = H(f)\, C_\varepsilon\, \overline{H}(f)' \tag{2}$$

where $\overline{H}'$ is the transposed complex conjugate of the matrix $H$, and $f$ is the frequency range, from 0 to the highest frequency available (corresponding to $1/(2TR)$ Hz). The matrix $H(f)$, which describes the transfer functions (response in frequency) of a system of processes of white noise $\varepsilon_t$ to a system of time series $Z_t$, is given by

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$$H(f) = \left( I - \sum_{k=1}^{p} A(k) \exp(-i\,2\pi f\,k) \right)^{-1} \qquad (3)$$

where $I$ is the identity matrix. The power spectrum matrix, $P_z(f)$, in which the main diagonal $P_{ii}(f)$ and the other elements $P_{ij}(f)$ represent the power spectrum of the $i$ time series $z_{i,t}$ and the cross power spectra between $z_{i,t}$ and $z_{j,t}$, respectively. To be valid, the MAR model requires that the white noise process must be mutually uncorrelated, that is $C_\varepsilon$ must be diagonal, as follows

$$C_\varepsilon = \mathrm{diag}(\sigma_1^2, ..., \sigma_d^2) \qquad (4)$$

Thus, (2) and (4) yield

$$P_{ii}(f) = \sum_{j=1}^{d} \left| H_{ij}(f) \right|^2 \sigma_j^2 \qquad (i = 1,...,d) \qquad (5)$$

This indicates that the power spectrum of $z_{i,t}$ at the frequency $f$ can be decomposed in $d$ terms $\left| H_{ij}(f) \right|^2 \sigma_j^2$ $(i = 1,...,d)$, which can be considered as the contribution of the process with white noise $\varepsilon_{j,t}$ on the power spectrum of $z_{i,t}$, via the transfer function $H_{ij}(f)$. Finally, the RPC is defined as the relationship among each contribution to the power spectrum $P_{ii}(f)$, that is

$$R_{j \to i}(f) = \frac{\left| H_{ij}(f) \right|^2 \sigma_j^2}{P_{ii}(f)} \qquad (6)$$

Thus, the RPC values are computed for each pair $i$ and $j$, and at each frequency $f$. Each RPC value represents the power contribution of variable $j$ upon variable $i$. A RPC value of 0 indicates no influence of $j$ over $i$; while a value of 1 implies that $i$ is totally regulated by $j$ at the given frequency. In practical terms, a value of 1 would indicate that the process $j$ with the characteristic frequency of interest occurred before or induced the process $i$. Thus, the RPC methodology can help on delineating sequences of events or cause-effect relationships among the variables involved in the analysis.

## DESCRIPTION AND ANALYSIS OF THE TRANSIENT EVENT

In this work, it is analyzed a transient event where a pressure regulator of an electro-hydraulic system in a turbine failed. Power signals were obtained, along with other signals from diverse equipment and systems.

The RPC methodology is applied to eight signals, so a more detailed analysis of the frequencies of interest can be performed, and the tracking of such frequencies in the signals can delineate better the probable sequence of events in the transient, and possible cause-effect relationships and feedback mechanisms. The signal used in the analysis are: a) average reactor power (POW); b) flow through reactor core (TFC); c) pressure drop across the core (DPC); d) feedwater flow (FFW); e) flow through jet pumps on both recirculation loops (JPF); f) flow through each recirculation pump (RFW); g) power of each recirculation pump (PRP); and h) pressure drop on each recirculation pump (DPP). The sampling rate for all the signals was 5 Hz, and 3000 data points were used in the analysis.

First, a recursive algorithm to extract the DC and fluctuation (noise) components was applied. Thus, the signals analyzed have zero mean value. Then, the noise signals are input to the MAR model, and from it the AR coefficients were obtained. Finally, the RPC values were computed. The full computation process is that explained in the previous section.

Figure 1 shows the reactor power signal and Fig. 2 its power spectrum density. From Fig. 1, it can be noted that the period for a full oscillation is about 18 seconds, that is, a characteristic frequency of 0.055 Hz, which can be noted as the main peak on Fig. 2. This frequency value, as mentioned before, is in the range of characteristic frequencies related to instabilities caused by actuation of some control systems. Also, although not as well defined, the frequency of 0.65 Hz can be noted. This value corresponds to characteristic frequencies related to void reactivity in the reactor core.

## RESULTS

Table I presents RPC results of the inter-relationship among the signals from the core and those only from the recirculation pump A. Similarly, Table II shows results when using signals from the recirculation pump B.

Table I shows that both the feedwater flow, setting aside the influence of a variable on itself, and reactor power have the strongest influence on the signals related to core variables. Note also that there exists only a modest contribution of the reactor power on the feedwater flow signal, but the contrary is true when looking to the impact of feedwater flow on reactor power. The contributions of the rest of the variables on feedwater flow and reactor power are negligible. It is also clear that the signals from variables related to the recirculation pump have negligible impact on the variables related to the reactor core. Similar results are shown in Table II, for the case of using signals from variables related to the reactor core and signals from the recirculation pump B.

The results on Tables I and II show a clear relationship between feedwater and reactor power for this transient event. Also, it is the feedwater that appears as the origin, considering only the signals available analyzed, of the disturbance that lead to the reactor power oscillation. Recalling that the transient was actually originated on the turbine system, the results just presented clearly support the fact that the disturbance firstly appeared on the feedwater flow, keeping in mind that it is the available signal coming from the closest system to the turbine system, and then transported to the reactor core, as shown on the contributions to the flow through

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the core, the pressure drop across the core, and even through the flow through the jet pumps, where the feedwater and recirculation flows mix, to finally impact upon the power, and thus causing the oscillations. Then, once the power started to oscillate, a feedback loop was completed.

Although already described, it is important again to stress that there is no influence of the reactor power and feedwater flow, in fact from none of the variables related to the core, on the variable related to the recirculation pumps, and vice versa. This is to be expected since no relation exists between feedwater flow and recirculation flows, because they are physically separated systems and the flows only mix at the jet pumps. The RPC methodology, therefore, has produced results quite in agreement with reality for both the cause-effect relations, and their feedback loops, and the independence of events or systems.

## CONCLUSIONS

The RPC methodology has been confirmed as a reliable and useful tool for determining inter-relationships, or not, among different events or systems during transients, their feedback mechanisms, and delineating sequences or cause-effects relations between events developing during the transients

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Table I. RPC results for the signals from reactor core signals and recirculation loop A at the frequency 0.055 Hz.

| | POW | FFW | TFC | DPC | JPF | PRP | DPP | RFW |
|---|---|---|---|---|---|---|---|---|
| POW | 0.23208 | 0.70988 | 0.00271 | 0.02338 | 0.0074 | 0.01876 | 0.00251 | 0.00326 |
| FFW | 0.08658 | 0.87363 | 0.00148 | 0.0077 | 0.01356 | 0.01133 | 0.00185 | 0.00386 |
| TFC | 0.39026 | 0.39349 | 0.1302 | 0.02324 | 0.05102 | 0.00652 | 0.00464 | 0.00063 |
| DPC | 0.21207 | 0.26713 | 0.00333 | 0.44554 | 0.0139 | 0.0535 | 0.00409 | 0.00043 |
| JPF | 0.17025 | 0.17337 | 0.00264 | 0.01743 | 0.54743 | 0.04952 | 0.03633 | 0.00304 |
| PRP | 0.00705 | 0.00892 | 0.00574 | 0.01239 | 0.03051 | 0.92314 | 0.00805 | 0.00419 |
| DPP | 0.02857 | 0.03826 | 0.00195 | 0.02829 | 0.07361 | 0.09548 | 0.72901 | 0.00483 |
| RFW | 0.02309 | 0.03768 | 0.00076 | 0.00237 | 0.0031 | 0.00182 | 0.00077 | 0.93042 |

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Table II. RPC results for the signals from reactor core signals and recirculation loop B
at the frequency 0.055 Hz.

| | POW | FFW | TFC | DPC | JPF | PRP | DPP | RFW |
|---|---|---|---|---|---|---|---|---|
| POW | 0.27341 | 0.56347 | 0.00239 | 0.1429 | 0.0089 | 0.00527 | 0.00121 | 0.00244 |
| FFW | 0.12026 | 0.80651 | 0.00248 | 0.05804 | 0.00649 | 0.00273 | 0.00177 | 0.00174 |
| TFC | 0.3491 | 0.32221 | 0.24627 | 0.05257 | 0.01526 | 0.0084 | 0.00333 | 0.00286 |
| DPC | 0.09626 | 0.19952 | 0.01494 | 0.60256 | 0.02551 | 0.02779 | 0.02812 | 0.0053 |
| JPF | 0.0579 | 0.06903 | 0.1271 | 0.09701 | 0.62815 | 0.00174 | 0.01548 | 0.00359 |
| PRP | 0.03094 | 0.07705 | 0.00524 | 0.01923 | 0.03005 | 0.61951 | 0.21755 | 0.00043 |
| DPP | 0.04859 | 0.05541 | 0.00075 | 0.00188 | 0.01006 | 0.09342 | 0.7894 | 0.00049 |
| RFW | 0.02955 | 0.00147 | 0.00002 | 0.00738 | 0.00078 | 0.00387 | 0.03612 | 0.92079 |

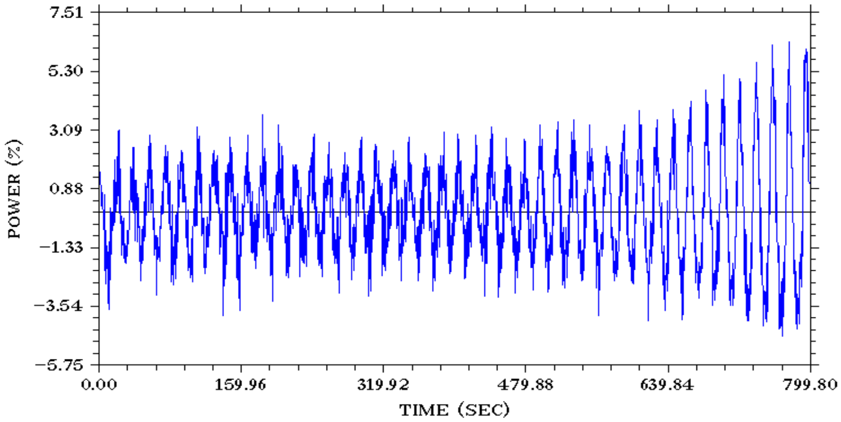

Figure 1. Reactor power signal.

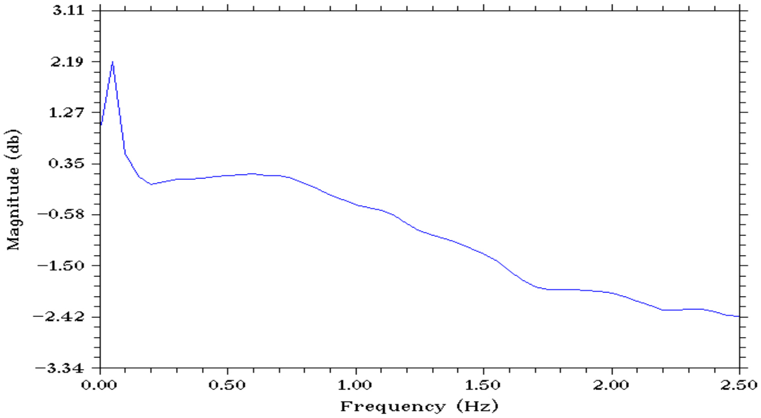

Figure 2. Power spectral density of the reactor power signal.

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