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AUTHOR(S): *HOWARD A. SMOLLECK, NEW MEXICO STATE UNIVERSITY (NMSU)*
SATISH J. RANADE, N.M.S.U.
HADIYURAM R. PRASAD N.M.S.U.
Rudolph O. Velasco, Los Alamos National Laboratory

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Los Alamos Los Alamos National Laboratory
 Los Alamos, New Mexico 87545

EFFECTS OF PULSED-POWER LOADS UPON AN ELECTRIC POWER GRID

Howard A. Smolleck Satish J. Ranade Nadipuram R. Prasad Rudolph O. Velasco
 Department of Electrical and Computer Engineering Los Alamos National Laboratory
 New Mexico State University Los Alamos, NM 87545
 Las Cruces, NM 88003

Senior Member, IEEE

Member IEEF

Member IEEE

Member IFEE

SUMMARY

Low-frequency cyclic loads have historically been present in industrial processes for many years. Such loads tend to be continuous-operating processes for which analysis has been documented. However, a related class of cyclic loads, involving large fusion experiments and related research, has more recently come under particular concern within the electric utility environment.

Pulsed loads associated with fusion processes are often characterized by significant energy demands, little or no regeneration, and frequencies which may be in the range of dominant dynamic system modes. Such loads have the potential to cause adverse effects such as voltage flicker, transient instability, dynamic instability, and machine shaft torsional mode excitation.

This paper describes a general approach for the assessment of the anticipated effects of large pulsed loads upon the electric power grid supplying an experimental facility, as well as upon local facility generation and utilization. Specific application is made to the network serving Los Alamos National Laboratory, under whose sponsorship the study was conducted. While the analysis techniques employed are, in themselves, not new, the total approach and assessment of the impact of pulsed-power loading on a large electric power system has not been concisely documented in released literature.

At least three main considerations must be addressed concerning any such proposed pulsed load: the ability of the utility service to supply the energy demand, the effects of the cyclic load upon local facilities (which may include sensitive subsystems such as local generation and computer devices), and the effects upon the larger utility grid. It is recognized that a particular system study of the scope and direction outlined here is, by its very nature, highly network specific. However, it is possible to establish an approach to analysis that is sufficiently general to enable its extension to other networks and loading situations.

In describing the impacts of periodic

pulse loading, both a screening tool and a set of detailed analysis procedures are necessary. It is desirable to furnish experiment designers with limitation guidelines, as well as to retain the capability of accurate assessment of the effects of a specific pulse. In doing this, it is convenient to think in terms of the spectral content of proposed pulse profiles and to relate this to the establishment of a total bound on pulsed loadings at a particular network location. This is done in the paper by means of a "spectral envelope," which enables the concise relation of allowable pulse magnitude and frequency content.

The paper discusses the use of transient and dynamic stability assessment, shaft torsional frequency and SSR considerations, and specific uses of both frequency- and time-domain analysis in the evaluation of such effects. A spectral envelope such as shown in Fig. 1 is developed in order to illustrate ranges of allowable pulse spectral content at a specified location.

Fig. 1. Spectral envelope showing limiting conditions for pulsed loads at Los Alamos National Laboratory.

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Department of Electrical and Computer Engineering Los Alamos National Laboratory
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Abstract - Certain proposed particle-accelerator and laser experiments, and other devices related to fusion research, require multi-megawatt, repetitive power pulses, often at low (subsynchronous) frequency. While some power-delivery technologies call for a certain degree of buffering of the utility demand using capacitive, inductive, or inertial energy storage, considerations have also been made for serving such loads directly from the line. In either case, such pulsed loads represent non-traditional applications from the utility's perspective which, in certain cases, can have significant design and operational implications.

This paper outlines an approach to the analysis of the effects of such loads upon the electric power grid using existing analysis techniques. The impacts studied include bus-voltage flicker, transient and dynamic stability, and torsional excitation. The impact of a particular pulsed load is examined and illustrated for the power network serving the Los Alamos National Laboratory.

KEYWORDS: Pulse power, pulsed loads, flicker, stability, transients.

INTRODUCTION

Low-frequency cyclic loads have historically been present for many years in the form of arc furnaces, smelters, and certain other heavy-industrial processes. Especially in recent years, their effects upon both system design and operation have been considered analytically [1,2,3]. Such industrial loads tend to be continuous-operating processes for which harmonic analysis is particularly appropriate [3].

A related class of cyclic loads has come under particular concern within the electric utility environment. Recent emphasis upon large pulsed-load experiments for fusion and related research, coupled with technological improvements in the power-handling and control capability of solid-state switches, have made such experiments of high power density feasible from the perspective of the experimenter. This has engendered a proliferation of experiment designs of large scale, often without due consideration for the consequences of their power requirements.

Pulsed loads associated with fusion re-

search and similar processes are often characterized by significant energy demands, little or no regeneration, and frequencies which may be in the range of dominant dynamic system modes. An example of a pulsed power waveform, as actually proposed for an accelerator experiment, is shown in Fig. 1. There is a strong possibility that such loading will have adverse consequences in an otherwise well-damped system. At least three main considerations must be addressed concerning any such proposed pulsed load: the ability of the utility service to supply the energy demand, the effects of the cyclic load upon local facilities (which may include sensitive subsystems such as local generation and computer devices), and the effects upon the larger utility grid.

This paper, whose primary goal is to explore and illustrate the impact of pulsed loads, describes a general approach for the assessment of the anticipated effects of large pulsed loads upon the electric power grid supplying an experimental facility, as well as upon local facility generation and utilization. While the analysis techniques are, in themselves, not new, the total approach to the assessment of the impact of pulsed-power loading on a large electric power system has not, to the authors' knowledge, been expressed in concise formulation in the literature.

The work cited here was supported by Los Alamos National Laboratory (LANL) for whose network and loadings the analysis is performed [4,5]. It is recognized that a particular system study of the scope and direction outlined here is, by its very nature, highly network specific. However, the approach is sufficiently general to enable its extension to other networks and loading situations.

Effect of Pulse Loading on Utility Systems

The primary effects of pulse loading are manifested in the areas of

- (1) voltage flicker
- (2) transient stability
- (3) dynamic stability
- (4) excitation of torsional frequencies in generators

Each of these areas of study is discussed later in this paper. However, it is helpful to first relate them conceptually to the problems of establishing a total bound on pulsed loadings at a particular network location. The authors have chosen to do this by introducing the concept of a "spectral envelope."

THE SPECTRAL ENVELOPE: A SCREENING TOOL

In describing the impacts of periodic pulse loading in general terms, it is convenient to think in terms of the spectral content of proposed pulse profiles. Fig. 1a shows one cycle of a possible repetitive load pulse of 24 Hz repetition rate, while Fig. 1b shows the

a. load pulse

Harmonic	Frequency (Hz)	Magnitude (A peak)
0	0	185.5
1	24	170.0
2	48	29.4
3	72	11.7
4	96	4.7
5	120	4.5
6	144	4.2
7	168	1.5
8	192	2.4
9	216	3.1

b. Corresponding spectrum

Fig. 1. A candidate pulse and its spectrum.

corresponding spectrum. The power associated with the load pulse may be considered to contain a certain set of harmonics (not to be confused with voltage and current harmonics). Pulse loading at each harmonic frequency results in a particular type of response. It should be emphasized that the net response of the (nonlinear) system is not a summation of the responses at the specific harmonic frequencies. However, it is necessary that the magnitude of each specific harmonic frequency not exceed the limit which would cause unacceptable response if the system were pulse-loaded at that frequency. Also, it should be noted that even if each harmonic were within limits the entire pulse may still produce an unacceptable response.

With this interpretation, it is logical to express limits on spectral content by means of a simple frequency-domain diagram such as conceptually shown in Fig. 2. The figure displays several bounding envelopes. For example, the allowable voltage flicker depends upon the frequency of the flicker; thus there is a limit to maximum amplitude of pulse loading at any frequency in terms of that parameter, the maximum loading being dependent in turn upon both power demand and power factor. Similarly, bounds are shown for other potential problems; namely, transient stability, dynamic stability and shaft torsional frequency excitation. The hatched (allowable) region is bounded by the composite envelope.

Comparison of the spectrum of a proposed pulse with such an envelope provides an approximate indication of the acceptability of the pulse as well as an indication of the type

of potential problem for which more detailed study is warranted. Conversely, such a diagram provides pulse power supply designers with an up-front guideline for allowable designs.

The diagram of Fig. 2 ignores phase relationships between harmonics. Also, it is possible that in some cases one harmonic might mitigate the impact of another. Therefore, the diagram (if such can be meaningfully quantified in terms of the relevant limiting parameters in any given case) should be understood to be a screening tool only, and any specific pulse must ultimately be studied by detailed simulation.

Fig. 2. Concept of spectral envelope.

THE STUDY NETWORK

The techniques discussed in this paper have been specifically applied to the LANL system and its interconnections, the principal relevant parts of which are shown in Fig. 3.

Los Alamos National Laboratory is located in a somewhat remote area, relatively far from major generation and load centers. The facility is presently connected to the external grid by two transmission lines at 115kV, although a loop feed at 345kV has been considered. Three local steam generation units of 22.5 MW combined rating are present at the facility, with additional hydroelectric facilities of 8.8 and 12.6 MW located within 100 circuit-miles. The connection point of the anticipated pulsed load is electrically close to the local steam generation units.

The model of Fig. 3 was developed from the full network description found in the Western Systems Coordinating Council (WSCC) database. Several levels of network reduction were used in the analysis, including systems of 43, 33, and 3 buses. The study was directed primarily toward an examination of the impacts of proposed pulsed loads at the LAMPF bus upon the behavior of synchronous machines and other devices at the local gas-fired steam generation facility TA3, the hydro facilities ELV and ABQ, and a remote plant of interest (represented by the equivalent machine SJU).

The Los Alamos study was prompted by such factors as the relative proximity of critical generation units and large computer facilities to the pulsed load and the expectation of load pulses of various magnitudes, waveshapes, and frequencies requiring separate analysis. Also, the availability of the planned 345 kV loop feed has been open to question. Thus, a simple and versatile methodology, suitable for easy adaptation to system change, was desired from the outset of the study.

Fig. 3. System model showing significant buses

VOLTAGE FLICKER

One adverse effect of pulsed loading is voltage flicker. An approximate estimate of voltage flicker may be established in terms of steady-state bus voltage drop. Here, the load pulse is treated as a steady-state load with no consideration of transient- or dynamic-stability consequences. When compared with allowable flicker limits, the results of such a study yield an upper bound on pulse magnitude in terms of the voltage flicker parameter alone.

Subjective criteria to be followed concerning "acceptable" levels of flicker in terms of magnitude and frequency can be deduced from published references [6,7,8,9,10]. They represent observations by groups of human subjects and, more recently, observations of the effects of voltage dip upon electronic devices.

When the frequencies of the pulsed loads under study are small compared with line frequency, the pulse can be treated as a repetitive switching operation between two steady-state load levels for the purposes of the voltage flicker study. For each load level and power factor, a power-flow run is made and the bus voltage magnitudes compared with corresponding values for the base case (zero pulsed load). The following assumptions hold for each part of such a study:

- (1) Percent voltage drop is defined with reference to the voltage at the bus under projected normal system load conditions as determined by a load forecast and power-flow study.
- (2) The pulsed load is modeled in the power-flow study at a constant MVA level, and the voltage flicker is determined by comparing the resulting bus voltage with that at zero pulsed load.
- (3) No LTC or other taps are changed during the switching of the load in question. Taps are set to match the base case expected prior to any pulsing and it is assumed that LTC's could not be operated quickly enough to avert noticeable voltage dips where present.
- (4) Local site generation is fixed at the base-case level, and no tie-line control is exercised between control areas.

Typical results, for four values of load power factor, are shown in Fig. 4a for the TA3 13.8kV bus. As expected, it is seen that the system will tolerate higher values of pulsed load MVA for higher power factors. Furthermore, it is certain that flicker values will increase for contingencies such as the loss of an important line near the load.

An analysis such as this, which is relatively simple to perform, can be used to identify the most sensitive or susceptible system buses with regard to voltage flicker and to specify maximum bounds on pulse loading in terms of that study parameter. Using curves of allowable flicker, such as found in [6] or [7], and data such as that of Fig. 4a, a spectral envelope of maximum allowable MVA (or MW) content vs. frequency content can be drawn. Fig. 4b, which corresponds to Fig. 4a, is an example of such a curve.

Fig. 4a. Voltage flicker (in V on 120V base) for various switched MVA loadings at several values of power factor (345 kV feed included).

Fig. 4b. Flicker bound of spectral envelope at TA3NA 13.8kV bus, corresponding to Fig. 3.

In practice, pulsed loads will not normally be repetitively switched between minimum and maximum demand limits but will follow some defined time function such as that of the example shown in Fig. 1. Depending upon the rise time, pulse frequency, and other factors, actual pulsed loads can exhibit a greater effect upon bus voltage flicker than predicted

through power-flow studies. This is shown below. Despite the approximations, however, voltage flicker criteria developed from power-flow studies are useful for several reasons:

(1) They help quantify one type of upper bound upon allowable switched MW (or MVA) in terms of acceptable voltage flicker.

(2) They are independent of the actual pulse waveform, and thus provide another (and easily-determined) bound on the allowable switched load.

Transient Effects of Flicker: an Example

It is evident that caution must be exercised when extrapolating conclusions from the results of applying techniques such as the above which are based upon steady-state analysis assumptions. Often an actual time-domain simulation (usually conducted on the basis of a three-phase representation of a reduced network model with relevant elements modeled in detail) is necessary. An Electromagnetic Transients Program (EMTP) [17] analysis of the same example will illustrate this.

Consider the load pulse of Fig. 1a, which appears on the low-voltage side of a 115/13.8 kV transformer located at the LAMPF bus of Fig. 3. The pulse, shown as a negative current in Fig. 5a, is energized at 50 ms in the EMTP simulation with logarithmic smoothing to prevent numerical oscillation. The resulting rms bus voltage deviation in per-unit from 1.0 per-unit appears in Fig. 5b.

At the onset of the pulse, it is evident from Fig. 5b that the voltage begins to drop. However, the pulse voltage then recovers and then goes above 1.0 per unit. It can be shown [5] that the maximum excursion of rms bus voltage predicted by this simulation is greater than that predicted by flicker analysis.

This can be explained with recourse to the simple equivalent network of Fig. 6, in which a sinusoidal pulse current is supplied by the source

$$i_p = I(t) \sin \omega t \quad (1)$$

where $I(t)$ is the pulse profile. It can be shown [5] that the voltage V_p can be expressed in instantaneous form as

$$v_p = V \sin \omega t - L \frac{di_p}{dt}$$

or in rms

$$V_p = \frac{V}{\sqrt{2}} - \left[\frac{L}{\sqrt{2}} \frac{dI(t)}{dt} \right] - \frac{j\omega L I(t)}{\sqrt{2}} \quad (2)$$

The bracketed term represents the additional voltage due to the rate of change of the pulse. The effect of this term is evident in the example of Fig. 5b. Thus, while power-flow studies can help to bound the allowable pulse, consideration should be given to the additional effect of pulse rate of rise.

TRANSIENT STABILITY

Transient stability refers to the ability of synchronous machines in a power system to remain in synchronism after a large disturbance such as a fault or a sudden change in load. A system is considered to be "first-

(a)

Fig. 5. Pulse Profile and resulting rms bus voltage deviations.

Fig. 6. Explanatory equivalent network.

swing stable" if the machine relative angles begin to converge. First-swing stability, which typically spans a period of about 1 second, is often taken to be indicative of transient stability as a first approximation [12,13].

Transient stability is typically evaluated by time-step simulation in which voltages and currents are expressed as phasors. In transient-stability analysis, therefore, simulated pulsed loads are restricted to frequencies somewhat lower than line frequency, and intra-cycle (from a line-frequency point of view) effects are masked.

If the magnitude of pulse loading is not excessive, the primary impact of the pulse is manifested upon local generation in the form of motoring or loss of synchronism.

As illustrated presently, a straightforward application of the equal area criterion can yield a transient-stability upper bound on permissible step load change. This upper bound can be related to the maximum amplitude of pulsed load as follows:

(1) For pulses of short duration and low repetition rate each pulse appears as a step load change and the amplitude must be limited to the permissible step change.

(2) For higher repetition rates, the average value of the load should not exceed the step change limit.

A simple bound on permissible step load change can be developed through a straightforward application of the equal-area criterion. Consider the system shown in Fig. 7a, which shows a local generator connected by an equiv-

alent reactance x to a "stiff" power grid which is modeled as an infinite bus. The pulsed load is electrically close to the local generator, and is modeled as a switched resistive load of conductance G at the terminals of the machine. It is desired to assess the probable effect of the pulsed load upon the local generator.

Before inception of the load, the electric power output of the local machine is given approximately [12] by the familiar relation

$$P_e = (1/X) \sin \delta = P_{\max} \sin \delta \quad (3)$$

where the transient internal voltages have been assumed to be 1.0 per-unit, and with reference to Fig. 7a,

$$X = x'_d + x \quad (4)$$

where

x'_d = transient reactance of local machine.
 x = system short circuit impedance seen at the machine terminals.

Equation (3) is shown as curve a in Fig. 7b.

Closing the switch S simulates a step load change and shifts the power angle curve. Assuming $G \ll 1/x$, and noting that generally, for machines of small capacity, $x \ll x'_d$, it is shown in [5] that the power angle equation becomes

$$P_e = P_{\max} (\sin \delta + GX) \quad (5)$$

This can be visualized as curve b in Fig. 7b. The stability of the system can now be studied by using the equal area criterion [13] in conjunction with Figure 7b.

Fig. 7a. Simplified 3-bus model.

Fig. 7b. Explanation of transient stability effects.

It can be shown [5] that the system is stable if some value of $\delta_{\max}$ can be found such that the equation

$$1 - \cos \delta_{\max} = GX \delta_{\max} \quad (6)$$

can be solved. Obviously, a limit (at least theoretical) of pulse magnitude exists beyond which first-swing stability is not preserved. For the subject system the pulse load limit is approximately 700 MW. At this loading the voltage would collapse and thus voltage stability is the limiting factor.

Accurate values of the limits discussed above can be determined by a series of stability studies, such as the following, made upon the network in question:

--A study to determine the maximum allowable step load change.

--A study to determine the peak amplitude of square pulses of low duty cycle in the low (0-3 Hz) frequency range, with duty cycles to about 0.5.

An example of the use of a production-grade transient stability program with full network representation, detailed machine models, and a detailed pulse model is illustrated in Fig. 8. Here, a pulse having the waveform of Fig. 1a, with a 10 MVA peak at 0.9 PF lag and a repetition rate of 2.1 Hz, is applied at the LAMPF bus. Rotor velocity deviation at one of the TA3 machines is being examined.

It can be seen that the impact of this pulse on the local generator is insignificant in view of the high transient stability limit established earlier. That result is expected. Note, however, that a dynamic mode at 2.1 Hz is clearly excited. This is discussed in the next section.

Using a range of such studies it is possible to develop bounds on the allowable pulse magnitude, for a given waveform, in terms of the transient stability of the system.

Fig. 8. Illustration of transient-stability result.

DYNAMIC STABILITY

Dynamic or long-term stability, by definition, relates to the ability of a system to remain stable during the period when generator swings are primarily dictated by the response

of their control systems [12]. Its study, which presupposes that the system has already been determined to be transiently stable, involves an analysis of the stability of the system under small operating-point changes; i.e. the dynamic response of the various generating units to small-scale system perturbations. As before, the perturbations of interest here are the pulsed loadings. Two related effects are of interest: the free response of the system (independent of the form of the forcing function) and the response of the system to the continued application of the pulsed load. Both of these effects are dependent upon system load and generation profiles.

Dynamic stability can be assessed using both frequency-domain and time-domain methods. In the frequency-domain method, using classical linear system theory, the system can be represented by a state-variable model of the form

$$\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u} \quad (\text{state equations}) \quad (7)$$

$$\mathbf{y} = \mathbf{C} \mathbf{x} + \mathbf{D} \mathbf{u} \quad (\text{output equation}) \quad (8)$$

where

$\mathbf{x}$ = the state vector

$\mathbf{y}$ = output vector

$\mathbf{A}$ = coefficient (characteristic) matrix

$\mathbf{B}$ = input matrix

$\mathbf{C}, \mathbf{D}$ = output matrices of coefficients

$\mathbf{u}$ = forcing input.

Eigenvalues determined from the $\mathbf{A}$ matrix of (7) yield estimates of both the damping and oscillatory frequencies of the system. Note that the above analysis corresponds to linearizing the system about an operating point, which is typically obtained from a power-flow analysis of the system for a specific set of network injections and topology.

Having estimated the eigenvalues, the response can be verified through transient-stability simulations. Here, the system is perturbed at specific natural frequencies as determined from the eigenvalue estimates, and at the pulse frequency.

If a system is perturbed at a specific natural frequency, sustained oscillations will always develop. If the frequency is lightly damped, the magnitude of such oscillation will be large. Such a study yields a forced response which includes all modes with the excited mode sustained. This kind of analysis is a useful step in verifying whether sustained oscillations are likely to be developed at lightly-damped frequencies in a system.

An example is illustrated in Figs. 9 and 10 for a model of the study system comprising 4 generating units. Referring to Fig. 9, which illustrates the eigenvalue estimates, it is observed that the dominant frequency is approximately 2.1 Hz and the corresponding damping value is relatively small when compared to the other system eigenvalues. Perturbing the study system at this frequency using a conventional transient stability modeling approach produces the time responses shown in Fig. 10, which illustrates the electrical power output for the three smallest units in the model (the fourth is essentially an infinite bus). It is interesting to note from Fig. 9 that continuously perturbing the system at 2.1 Hz not only allows the identification of a specific unit that participates at this natural frequency but also provides a validation regard-

ing the accuracy of the eigenvalue estimates. During the presence of the perturbing input the other on-line generating units do in fact respond to the system transient but ultimately settle down to negligibly small excursions about their pre-disturbance outputs. The prominence of a single unit (here, TA3) in its response to this perturbation is evident.

Another means of analyzing the dynamic stability behavior using a frequency-domain approach is commonly used. In this approach, the basic idea is to compute the steady-state oscillations which result from an external forcing function applied to a linear system model [14, 15, 19]. The forcing function is typically a torque perturbation on the generator shaft. The solution technique used in this approach is an iterative technique [15]. Fig. 11 illustrates the response when the largest unit (SJU) modeled in the study system is perturbed in this manner. The resonant frequencies, marked in the diagram, are evident. Note that these frequencies correlate extremely well with those identified earlier.

The rise time of the 24 Hz pulsed load waveform of Fig. 1 is sufficiently great so as to effectively impress an impulse upon the system. Such would be equivalent to stimulating all of the natural frequencies of the system. The repetitive nature of the pulse therefore has the effect of amplifying the generator torques with the result that a lightly-damped mode may continue to be excited.

The methodologies identified in this paper for examining dynamic stability issues are indeed complementary to one another and should yield similar results in well-formulated cases. Other methods such as the singular perturbation technique [16] may also be used to clarify and/or substantiate the oscillatory behavior of pulsed loading on power systems.

TORSIONAL MODE EXCITATION

Pulsed loads can excite the torsional modes of turbine-generator systems in certain situations. This phenomenon is well known in relation to subsynchronous resonance (SSR), which is usually associated with series-compensated transmission systems. Two effects are generally distinguished:

(1) Series compensation and line reactance can combine to produce an electrical resonant frequency that is usually less than 60 Hz. At such a frequency a synchronous machine acts as a (negative-resistance) induction generator. If net circuit resistance becomes negative, the subsynchronous current and voltage can grow without bound and produce large torque stresses on the turbine/generator as a unit (the so-called "induction generator" effect).

(2) Even if the electrical frequencies are well-damped, system disturbances can lead to excitation of a specific mode (the "torque amplification" effect).

If the resulting resonant frequency coincides with one of the torsional frequencies of the shaft system (at which the natural damping is extremely small) the torsional oscillations can become extremely large, resulting in shaft torsional fatigue [18].

Pulsed loads can create an SSR-like situation in that they can excite resonant fre-

EIGENVALUES

OSCILLATION FREQUENCY (HZ)

LAMBDA (1) =	-0.00625 ± j	0.33738	2.11980
LAMBDA (5) =	-0.06214 ± j	0.22176	1.39339
LAMBDA (8) =	-0.0276 ± j	0.26991	1.69592
LAMBDA (11) =	-0.30036 ± j	0.00021	0.00132
LAMBDA (14) =	-0.29336 ± j	0.00017	0.00107

Fig. 9. Estimated eigenvalues for study system comprising 4 generators.

Fig. 10. Time response of generating units to a 2.1 Hz system perturbation.

quencies of series-compensated lines or directly excite the torsional modes of the system if such frequencies are equal to or multiples of pulse load frequency. For this reason, such frequencies should be avoided.

The latter effect is of prime interest in the case of the subject system. This is illustrated in the EMTF-based simulation of Fig. 12. Here the effect is rather well damped.

LIMITS ESTABLISHED FOR SUBJECT SYSTEM

To complete the example for the subject system of this paper, a total spectral envelope identifying the boundaries for allowable pulsed load at the LAMPF bus in terms of amplitude and frequency is shown in Fig. 13. Bounding factors include voltage flicker, transient stability, and oscillatory modes found to be prominent in the system.

Dynamic and torsional modes are shown simply as lines at their respective frequencies. Once these modes have been identified, further refinement of the spectral envelope around these frequencies can be made. This requires that the maximum amplitude of acceptable torsional oscillation be established, and also necessitates an accurate characterization of the damping of the mode. In practice, however, these two items cannot usually

Fig. 11. Estimated magnitude of speed deviations to speed perturbations at SJU unit.

Fig. 12. Illustration of excitation of shaft frequencies.

be accurately determined and therefore, for present purposes, the modes are merely shown as lines indicating spectral components to be avoided.

From Fig. 13, it can be seen that the candidate pulse at the level indicated poses no evident problem. However, it must be stressed that system response should be evaluated for any candidate pulse having spectral components near a boundary or a sensitive area (such as a dynamic mode).

Fig. 13. Spectral envelope for study system.

CONCLUSIONS

Repetitively-pulsed loads of high power or energy density pose unique problems to electric utility systems. This is especially true in the case of large proposed fusion experiments, which often require high energy densities at continuous repetition rates which may lie within sensitive ranges with regard to machine dynamics and flicker tolerance. Such problems are aggravated when the loads are located electrically remote from major generation centers, as is the case at Los Alamos.

Disturbances such as these have the potential to create several problems, e.g.,

- Voltage flicker
- Dynamic instability
- Transient instability
- Torsional mode excitation

In general, a combination of analysis techniques is employed in order to adequately address the potential problems cited above. The primary simulation tools are power-flow and transient-stability analysis and both time- and frequency-domain simulation. Detailed machine models should be employed; however, reduced network modeling is often appropriate [3].

The concept of the spectral envelope was introduced in order to concisely express the bounding limits on the candidate pulse. Such limits, which are obviously both system- and site-specific, can be established through the use of the analysis techniques described. The same techniques can be used for more detailed

simulation of the effects of a particular candidate pulse as required (which should certainly be done for any case which lies near a bounding limit). Thus, the central objective of the developmental effort outlined in the paper can be considered twofold:

- (1) To provide a screening tool which will allow (for a given system, load location, and set of operating conditions) an initial determination of whether a candidate pulse is likely to pose problems; and
- (2) To identify the requisite techniques for providing a more detailed assessment of the effects of a candidate pulse if preliminary analysis suggests that this is necessary.

In general, it is prudent to evaluate the effects of a specified pulse in each of the areas cited earlier, unless previous work demonstrates that certain analysis components are not required or that the corresponding bounds are high. For example, simple transient-stability studies using relatively small reduced models have demonstrated that the transient stability limit for faults or switching operations in the study system of this paper is considerably higher than the anticipated pulsed loads. This observation was found to agree with local utility experience. Thus it could be stated that transient stability, per se, is not a factor of concern for the Los Alamos loadings. As a word of caution, however, it should be kept in mind that one or more of the problems listed above can combine with others to produce undesirable system operations, ultimately leading to outages of system elements.

An analysis of the likely effects of pulsed loading upon a particular electric power network has been illustrated. It should be noted that the results of such studies are highly system-dependent. However, the basic procedures are applicable to other similar installations.

It has been the intent of the present paper to outline key concepts and general classes of required analysis methodologies, rather than to present an exhaustive discussion of these techniques. In general, the analysis methodologies cited are well represented in the literature. The authors are, however, preparing a second paper in this area in which the physical and mathematical bases of the present work are developed in considerably more detail.

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Howard A. Smolleck (SM) received the B.S., M.S., and Ph.D. degrees from the University of Texas, Arlington, in 1969, 1970 and 1975 respectively.

From 1974 to 1979 he was on the faculty of Old Dominion University, Norfolk, VA, and since August 1979 has been with the Department of Electrical and Computer Engineering at New Mexico State University, Las Cruces, where he currently holds the rank of Professor. His research interests include electric power system analysis, electric machinery, and the development of algorithms for the solution of large networks. Dr. Smolleck is a member of Tau Beta Pi, Eta Kappa Nu, Alpha Chi, and is a Registered Professional Engineer in New Mexico.

Satish J. Ranade (M) received the B.Sc. degree from Sagar University (India), the B.E. degree from the Indian Institute of Science, the MSEE from New Mexico State University, and a Ph.D. from the University of Florida in 1973, 1976, 1977, and 1981, respectively.

He is currently an Associate Professor of Electrical and Computer Engineering at New Mexico University. His primary research interests are power systems modeling and control, photovoltaics, and power electronics/motor control. Dr. Ranade is a member of the IEEE Power Engineering and Industry Application Societies, and the IEEE Working Group on Harmonics. He is also a member of ASEE, Eta Kappa Nu, and Tau Beta Pi.

Nadipuram R. Prasad (M) has over fifteen years experience in the power engineering field. From 1975-1985 he worked at American Electric Power where he was involved in various capacities in the Bulk Transmission Planning Division, and was manager of the System Dynamics Analysis Section. Presently, he is an Instructor in the Electrical and Computer Engineering Department of New Mexico State University, where he received the Ph.D. degree in 1989. His primary research interests are in the areas of control systems and the application of advanced artificial intelligence concepts to the operation and control environment of power systems.

Rudolph O. Velasco (M) served as part of the Special Engineers Detachment, Manhattan Engineering district, US Army Corps of Engineers, from 1943 to 1945. From 1974 to 1984 he was Chief of the Utilities and Engineering Division of the Zia Company, the utility contractor to Los Alamos. He is presently a Staff Member in the Facilities Engineering Division of the Los Alamos National Laboratory.

Mr. Velasco earned the BSEE degree from the University of Arizona in 1950 and the MS degree in Nuclear Engineering from the University of New Mexico in 1962. He is a Registered Professional Engineer in the state of New Mexico.