A Scheme for Controlled Islanding to Prevent Subsequent Blackout

S. Shahnawaz Ahmed, *Senior Member, IEEE*, Narayan Chandra Sarker, *Member, IEEE*, Azhar B Khairuddin,
Mohd Ruddin B Abd Ghani, *Member, IEEE*, and Hussein Ahmad, *Senior Member, IEEE*

***Abstract*—The power systems operated by the utilities in developing countries suffer from a large gap between demand and generation, inadequate transmission capacity, and nonuniform location of the load centers and generating stations. Occurrences of faults in such systems, in most of the cases, end up with the worst consequences (i.e., complete blackout). This paper illustrates the way a blackout can be prevented in real time through controlled segregation of a system into a number of viable islands together with generation and/or load shedding. The nature and location of any fault that warrants such islanding can be ascertained in real time through monitoring the active-power (megawatt) flows at both ends of a number of prespecified lines. The blackout of June 20, 1998 in the Bangladesh Power Development Board system has been used as an example in the illustration. The philosophy of the proposed islanding scheme may be considered for implementation in other power systems also.**

***Index Terms*—Power system control, power system modeling, power system protection, power system security, SCADA system.**

I. Introduction

THE POWER SYSTEM owned by Bangladesh Power Development Board (BPDB), the sole public utility for generation and transmission in Bangladesh, has evolved to a vulnerable position. The main reason is lack of funds for timely rehabilitation of the existing generation plants and transmission lines, and installation of new ones to meet a demand that increases every year by approximately 10%. Also, unavoidable concentration of the majority of powerstations in the country's eastern part, where indigenous gas and hydro reserves are located, has contributed to the vulnerability of this system. The consequent problems facing the operation of the BPDB system are drastic load shedding, lack of spinning reserve, low-voltage profile, and frequent [1] disruptions varying from wide-area outages to total blackouts. The most recent blackout in the BPDB grid system occurred on June 20, 1998. Such blackouts, needless to say, add to the inconveniences to consumers and cause irreparable loss to the national economy over and above what is caused by daily load shedding. Until now, no method has been devised by BPDB to avert these blackouts. If its system collapses for a fault, the generating units are restored one by one and synchronized with each other, taking almost a full day between the occurrence of the grid failure and the restoration of a sizable part. Also, considerable expenses are incurred in restoring the power plants from stalled conditions.

Incidents of several blackouts in grid systems of a number of developed countries have been reported in the literature [2]–[6]. The remedial measures suggested comprise generation shed, load shed, and islanding. It appears that splitting a grid system into a number of independent islands can be considered either as a last resort [2] or as a primary measure [5] depending upon the structure of the system. The basis for islanding is never unique but rather depends upon the utility in particular. In some systems [4], postfault oscillations of the generators are identified for their grouping before forming the boundaries of the islands against a specific fault.

However, for a more vulnerable system like the BPDB grid, an easy-to-implement and affordable method needs to be developed for islanding. The present paper proposes an islanding scheme with a focus on the following aspects:

i) investigation into the viability of post fault islanding at prespecified buses and lines of a grid system;
ii) determination of the criteria based on which the decision for islanding can be taken in real time and determination of the number of islands in order to avert blackout;
iii) supplementation of islanding by generation/load shed ding, subject to the nature and location of the fault.

The above aspects have been illustrated by analyzing the blackout of June 20, 1998, plus a few additional fault scenarios in the BPDB grid system.

II. Blackout of June 20, 1998 in BPDB Power System

The BPDB grid is comprised of 24 power stations connected primarily by a network of 132-kV transmission lines plus a few 230-kV lines. The grid area consists of two geographical zones: East and West, interconnected by a 230-kV double circuit line between GRSL—23 and ISHR—23 buses as shown in Fig. 1. The generated electricity is distributed to approximately four million consumers of various categories by BPDB itself, Dhaka Electric Supply Authority (DESA), and Rural Electrification Board (REB).

A. Blackout

On June 20, 1998 at 19:00 h (i.e., during the peak operation period) a total of 24 machines (some units within the same power station are considered as a single lumped machine) were generating 1970.5 MW to cater to a demand of 1918 MW, while

---

Manuscript received August 29, 2000; revised July 7, 2002.

S. S. Ahmed, A. B. Khairuddin, M. R. B. Abd Ghani, and H. Ahmad are with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Malaysia (e-mail: snahmed@suria.fke.utm.my; sahmed90@hotmail.com). S. S. Ahmed is on leave from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

N. C. Sarker is with the Instrumentation and Control Department, Siddhirganj Power Station, Bangladesh Power Development Board, Narayanganj 1430, Bangladesh (e-mail: narayansarker@hotmail.com).

Digital Object Identifier 10.1109/TPWRS.2002.807043

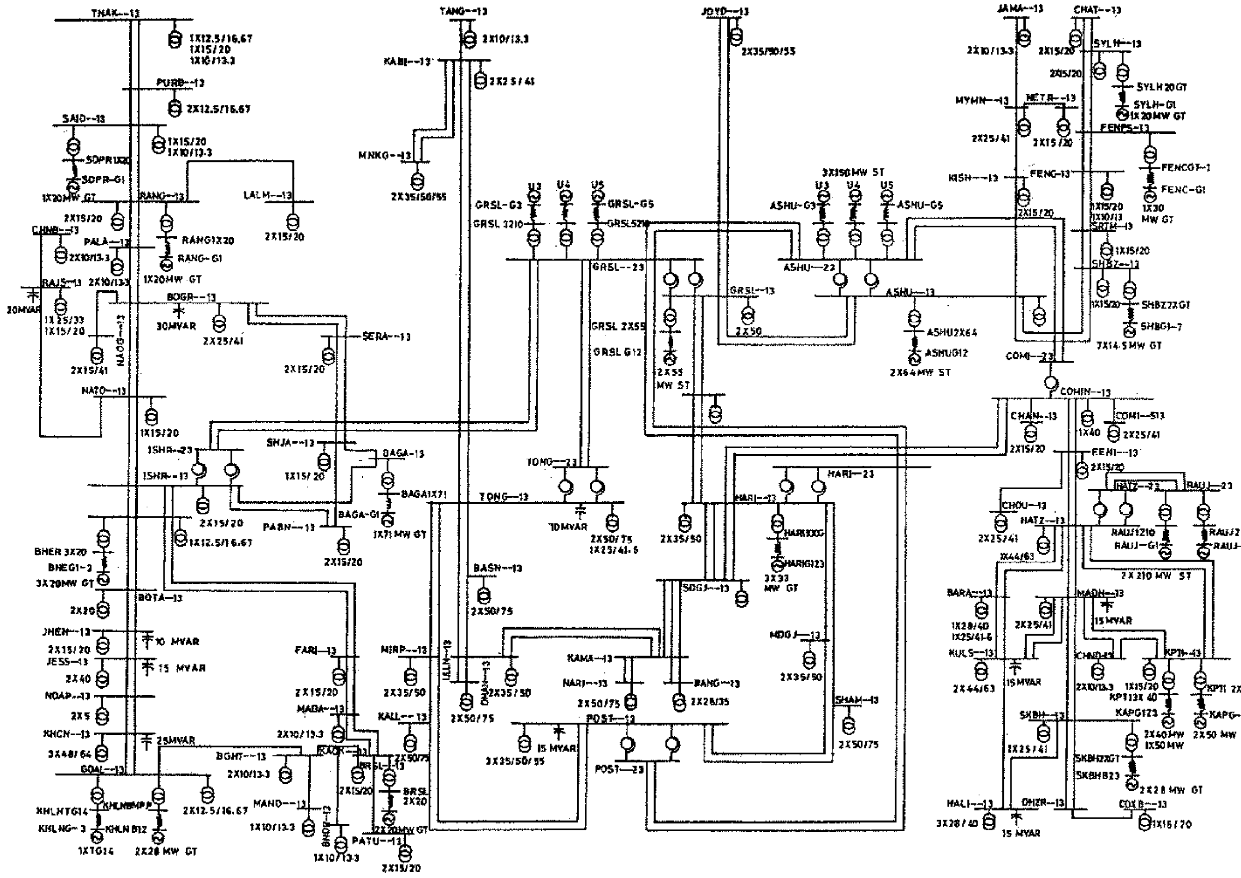

Fig. 1. Single line diagram of BPDB grid system.

another 171-MW demand could not be supplied at that moment. A total of 472 MW of generation capacity at different power stations was not available at that time primarily due to some units being out of service for maintenance.

The start of the blackout event on June 20, 1998 was marked at 19:10 h when both circuits of the 230-kV East-West Inter-connector (EWI) tripped while transmitting approximately 226 MW to the West zone. This tripping was followed by cascade outages of all the generators and tripping of a number of lines in the grid system. It was not known exactly where, when, and why the fault originated because no digital fault recorders were installed in the BPDB grid system. Therefore, to be aware of the events, information had to be collected from internal documentation such as the field reports and log sheets maintained in the load dispatch center (LDC), different power stations, and grid substations.

B. Restoration

The restoration process was started at 19:29 h, followed by another failure at 21:48 h. However, the process was finished at 06:38 h on June 21, 1998 (i.e., 11 h and 28 min after the occurrence of the blackout). But the generation for the day peak (10:00 h) and the evening peak (19:00 h) on June 21, 1998 was, respectively, 1604.7 and 1740.7 MW, which was less than the generation at the corresponding instants on June 20, 1998 before the blackout incident. It is obvious that a coordinated and prompt restoration is very difficult-to-achieve in a grid like the BPDB system, once it experiences a fault with no attempt to confine the effect within the fault's place of origin and the immediate surrounding area.

III. MATHEMATICAL MODEL

Upon occurrence of a fault on a line or at a bus in any part of a grid system, the balance between the mechanical power input to and the electrical power output from the synchronous generators is affected. As a result, the rotors of various machines oscillate noncoherently relative to each other, and they attempt to settle to a new stable equilibrium position. If they fail, the rotor angles continue to vary indefinitely from each other. Then the output frequencies of the machines, the power flows in the lines, and the voltages at the buses are subjected to nondiminishing swings resulting in cascaded outages in the system, which is the manifestation of the blackout phenomenon. A detailed analysis of the rotor swing angles, machines' frequencies, line flows, and bus voltages at the occurrence of the fault and after removing the same is typically done solving alternatively a set of algebraic equations and a set of second-order differential equations (e.g., by using a traditional transient stability program).

A multiport representation [7] shown in Fig. 2 for a power grid comprises a total of n buses in addition to the ground bus (0). The generator-connected buses are assigned the first m serial numbers among n buses $(m < n)$. Each generator has been represented [7], [8] as an emf source (having a constant magnitude E_i but a time-varying phase angle δ_i) in series with

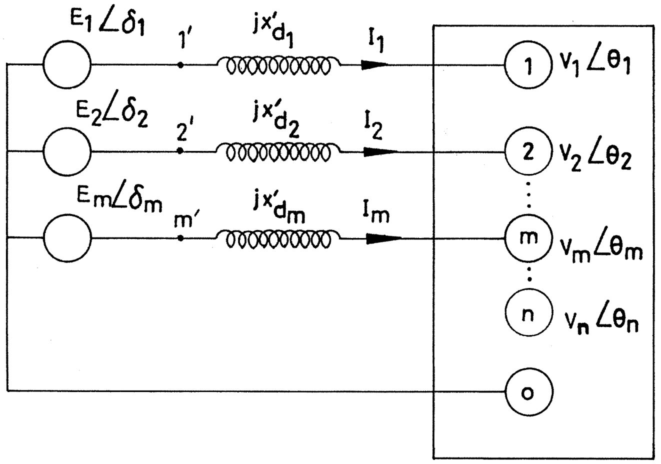

Fig. 2. Multiport representation of an n-bus power system with synchronous machines connected at the first m buses.

the respective direct axis transient reactance (x'_{di}) between the generator's internal bus i' ($i' = 1', 2', 3', \ldots \ldots \ldots m'$) and the system bus i ($i = 1, 2, 3, \ldots \ldots \ldots m$) . Also, the internal emf phase angle δ_i is considered [7], [8] to be the same as the angle of the corresponding generator's mechanical rotation. The given active and reactive load ($P_{load,i} + jQ_{load,i}$) at any bus i is converted into a constant shunt admittance $y_{load,i}$ and added with the corresponding diagonal term of the $n \times n$ system bus admittance matrix $[Y_{BUS}]$. The generators' direct axis admittances ($-j/x'_{\mathrm{di}}$) are added with the first m diagonal terms of the $[Y_{BUS}]$ matrix. As a result, the matrix $[Y_{BUS}]$ becomes an augmented matrix $[\hat{Y}_{BUS}]$ of the same size but with some of the diagonal terms changed.

The bus voltage $\overline{V}_i = V_i \angle \theta_i$ at any i-th bus is obtained from the solution of the bus voltage vector $[\overline{V}_{BUS}]$ as follows:

$$\left[\bar{V}_{BUS}\right] = \left[\hat{Y}_{BUS}\right]^{-1} \left[\bar{I}_{BUS}\right]. \tag{1}$$

The vector $[\bar{I}_{BUS}]$ comprises the current elements such that

$$I_{BUS,i} = \frac{-jE_i \angle \delta_i}{x'_{di}} \tag{2}$$

for $i = 1, 2, 3, \ldots \ldots \ldots m$ (i.e., generator-connected buses).

$$I_{BUS,i} = 0 \tag{3}$$

for $i = m+1, m+2, \ldots \ldots \ldots n$ (i.e., nongenerator buses).

The electrical power output P_{ei} of each synchronous machine connected at the buses $i = 1, 2, \ldots \ldots \ldots m$ is given by

$$P_{ei} = \frac{E_i V_i}{x'_{\mathrm{di}}} \sin\left(\delta_i - \theta_i\right). \tag{4}$$

The motion of the rotor of each synchronous machine at $t \geq 0$ ($t = 0$ is the instant of fault occurrence) is governed [7], [8] by the swing equation. Assuming negligible damping power this equation can be written as follows:

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} = P_{ai} = P_{oi} - P_{ei} \tag{5}$$

where

H_i	inertia constant of i-th machine in per unit of system base MVA;
f_o	system frequency in prefault condition;
P_{ai}	accelerating or decelerating power for i-th machine;
P_{oi}	mechanical power input to the i-th machine and considered to be equal to its output in the prefault condition neglecting losses.

From the time of fault occurrence ($t = 0$) to the time prior to fault clearance (t_{fc}) i.e., for $0 \leq t < t_{\mathrm{fc}}$, the admittance matrix $[\hat{Y}_{BUS}]$ in (1) is of dimension $(n - n_f) \times (n - n_f)$. The quantity n_f denotes the number of buses to be excluded because the fault occurs either at these buses or on the transmission lines near these buses.

From the instant of fault clearing ($t = t_{\mathrm{fc}}$) and thereafter (i.e., for $t > t_{\mathrm{fc}}$), the admittance matrix $[\hat{Y}_{BUS}]$ in (1) is of its original dimension (i.e., $n \times n$). Its diagonal terms corresponding to any bus i are recalculated if some generation/load is switched (shed or added) at that bus at $t = t_{\mathrm{fc}}$ so that $y_{load,i}$ changes as follows:

$$y_{load,i} = \frac{(P_{load,i} - P_{switch,i}) - j(Q_{load,i} - Q_{switch,i})}{V_i^2} \tag{6}$$

where

V_i	prefault magnitude of the i-th bus voltage;
$P_{switch,i} > 0,$	if some active load is shed;
$P_{switch,i} < 0,$	if some active generation is shed or load is added;
$0 < Q_{switch,i} < Q_{load,i},$	if some inductive load is shed;
$Q_{switch,i} < 0,$	if some reactive generation is shed or inductive load is added;
$0 < Q_{load,i} < Q_{switch,i},$	if net reactive load at i-th bus is to be made capacitive.

Also for $t > t_{\mathrm{fc}}$, the concerned diagonal and offdiagonal elements of the bus admittance matrix $[\hat{Y}_{BUS}]$ of (1) are recomputed appropriately to take into account the effect of the lines being either tripped for clearing the fault or removed for dividing the system into islands.

The constant emf magnitude E_i, initial phase angle δ_{0i}, and prefault power output P_{oi} for each generator are obtained from a load-flow solution [9] for the whole system in the prefault condition (i.e., at $t = 0^-$).

Equation (5) is solved at a small interval of time Δt for the swing angle δ_i and frequency f_i of each machine using the step-by-step method [10] after computing P_{ei} for all the machines using (4) and voltages at the various buses of the grid network using (1). For any instant of time $t = n\Delta t$ [i.e., the n-th interval ($n = 0, 1, 2, \ldots \ldots \ldots$ set limit)] the current vector $[\bar{I}_{BUS}]$ is formed using (2) and (3). The voltage vector $[\overline{V}_{BUS}]$ is obtained from (1) using the appropriate $[\hat{Y}_{BUS}]$ matrix corresponding to $t < t_{\mathrm{fc}}$ or $t \geq t_{\mathrm{fc}}$.

IV. PRESENTATION OF RESULTS

The mathematical model presented in Section III has been computer coded using FORTRAN 77. This is because commercial programs available are not in editable form (i.e., no source

TABLE I
PREFAULT BREAKUP OF GENERATION AND LOAD IN VARIOUS SECTIONS OF THE BPDB GRID SYSTEM AT 19:00 HRS ON 20TH JUNE 1998.

	Section Name	Jurisdiction	Generation		Load	
			MW	MVAR	MW	MVAR
East Zone	1. Chittagong	Greater Chittagong plus Feni and Choumuhani	465.00	450.80	369.00	179.00
	2. Sylhet	Greater Sylhet	121.00	62.60	76.00	37.00
	3. Dhaka	Greater Dhaka plus Greater Mymensingh and Comilla	1198.00	719.30	107.00	596.00
West Zone	4. Khulna	Greater Khulna plus Greater Barisal, Jessore and Faridpur	83.50	107.50	220.00	103.00
	5. Rajshahi	Rajshahi Division	103.00	102.00	176.00	80.00
Total			**1970.50**	**1442.20**	**1918.00**	**995.00**

code provided), and hence, cannot be customized to the specific input-output requirements of the present study such as information on islanding, load/generation switching, voltage, and line-flow profiles, etc. The coded program has been compiled and executed using Microsoft FORTRAN Power Station version 1.0 on a 225-MHz Pentium PC under a Windows 95 operating system. The obtained swing angles, voltages, line power flows, etc. have been retrieved from the output data files for constructing plots by the Microsoft Excel package.

The computer simulations have been made faster with less memory requirements by exploiting [11] sparse structures of the Jacobian matrices, and the augmented $[\hat{Y}_{BUS}]$ matrix. Jacobian matrices are used in the prefault load-flow analysis.

The stability study is preceded by a prefault load-flow solution of the BPDB system under the operating conditions existent at 19:00 h of June 20, 1998. The studied fault is considered to be occurring at $t = 0$ and cleared in four cycles (i.e., $t = 0.08$ s on 50-Hz basis). The step size used in the study is $\Delta t = 0.01$ s while the time span is from $t = 0$ to $t = 4.0$ s, which is usually [7], [8], [10] enough to confirm whether the rotor oscillations of various machines will settle or not. The results of the comprehensive study are presented, in the limited space of this paper, mainly in the form of general comments while highlighting the representative output data and plots.

A. Prespecification of Island Boundaries

As mentioned in section I, the present work has considered prespecifying the boundaries of the islands. This has been done on the basis of geographical proximity of the synchronous generators of the system, because the machines in the same geographical section oscillate coherently [12] when a fault occurs in the system. Depending upon the location and severity of a fault, the BPDB system can be divided into two to five completely separate islands. These islands are formed by five geographical sections—three of which are in the East zone and the remaining two are in the West zone, as shown in Table I. Island formation requires tripping the transmission lines existing between the sections. For reference, Table I also furnishes a section-wise breakup of the generation and load just prior to the blackout (i.e., at 19:00 h on June 20, 1998).

B. Stability Analysis for the Blackout Event

The blackout at 19:10 h of June 20, 1998 was simulated considering a three-phase fault on the EWI near its sending end bus GRSL—23.

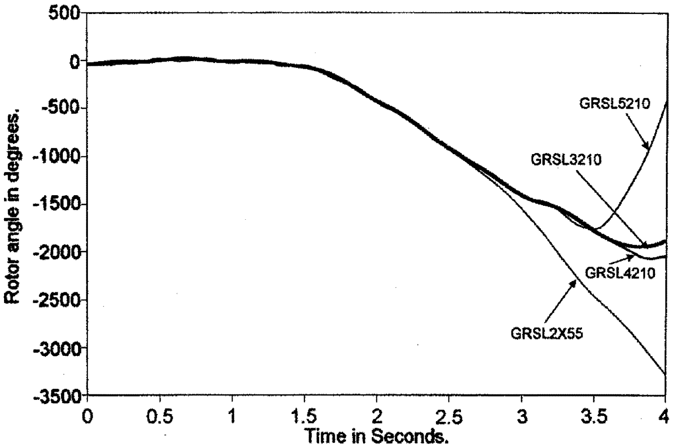

Fig. 3. Swings of some machines in island-1 (comprised by the East zone) relative to RAUJ1210 machine for the case of June 20, 1998 fault clearing with two islands.

1) Analysis With Two Islands: The applied fault was considered as cleared through a trip of both circuits of the EWI so that the grid system split into two islands, namely the East zone and the West zone. It should be noted that this case with two islands was what actually happened after the occurrence of the blackout. However, several attempts to achieve stability in each of the two islands with various combinations of generation shedding in the East zone (having a surplus prefault generation) and load shedding in the West zone (having a deficit prefault generation) failed. This instability may be seen from the machine swings shown in Figs. 3 and 4. The reason behind the failure with two islands is that while an attempt for a simple balance between "generation" and "load plus losses" may be effective under steady-state condition, it is not applicable for a system triggered into islanded conditions under a transient stability situation. In this condition, each island is subjected to different degrees of swings in bus voltages, line flows, and relative rotor angles of the machines. This may be mitigated through further islanding together with generation /load shedding in suitable proportion depending upon the prefault condition, fault location, and severity.

2) Analysis With Five Islands: The same fault was reanalyzed considering it as cleared through a trip of both the circuits of the EWI and removal of each circuit of all the lines between the five geographical sections mentioned in Table I. So in the after- fault condition, the grid was split into five islands. Bringing each of the islands individually to stable conditions required active (megawatt) generation and/or load shedding in

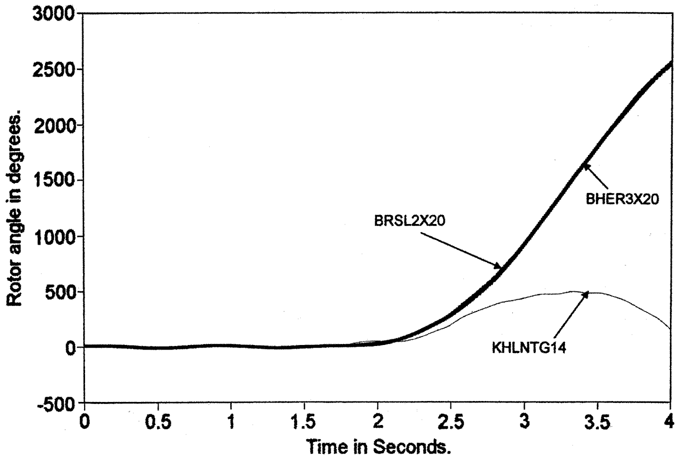

Fig. 4. Swings of some machines in island-2 (comprised by the West zone) relative to KHLNBMPP machine for the case of fault clearing with two islands.

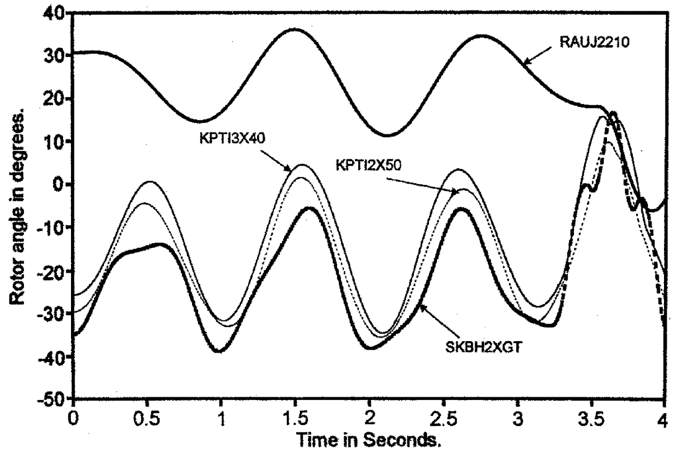

Fig. 5. Oscillations of some machines in island-1 relative to RAUJ1210 machine for the case of fault clearing with five islands.

various proportions. The percentage of "served load" to "generation" became approximately 99% in island –1, 89% in island – 2, and 98% in island – 3, all of which had surplus generation prior to the fault as may be seen in Table I. This percentage became approximately 64% in island – 4 and 59% in island – 5 each of which had a generation deficit.

The proportion of reactive volt ampere reactive (VAR) load and generation does not influence the transient stability directly. But to keep the bus voltage profiles within an acceptable range, for a brief period in an emergency situation, some VAR generation and/or load shedding may become necessary. Otherwise, voltage instability (i.e., voltage collapse), may occur which will affect power transferability from the machines. The present analysis showed that stability required MVAR generation and/or MVAR load shedding in some of the five islands so that the percentage of "served MVAR load" to "MVAR generation" became approximately 50% in island – 1, 59% in island – 2, 57% in island – 3, 47% in island – 4, and 71% in island – 5.

The rotor swing angles and frequencies of some of the machines, and the voltage profiles at some of the buses in islands –1 to 5 are shown in Figs. 5–12.

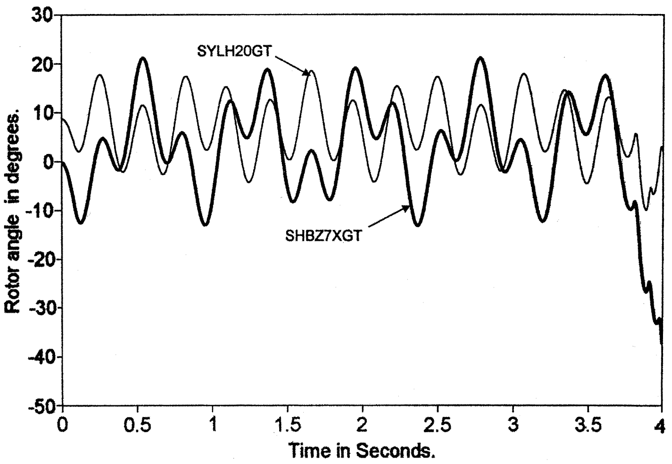

Fig. 6. Oscillations of some machines in island-2 relative to FENCGT-1 machine for fault clearing with five islands.

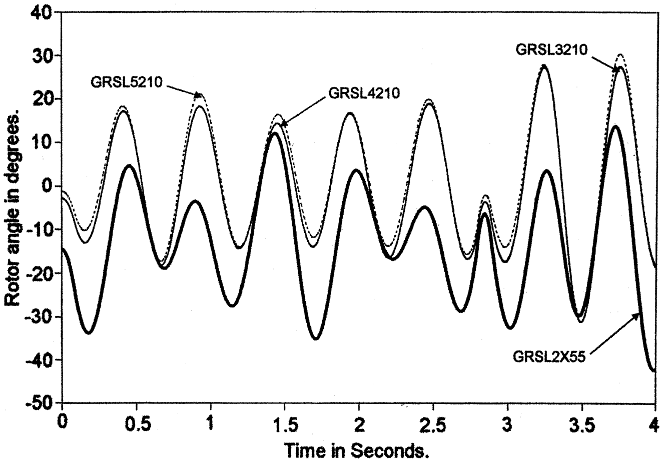

Fig. 7. Oscillations of some machines in island-3 relative to ASHU4150 machine for fault clearing with five islands.

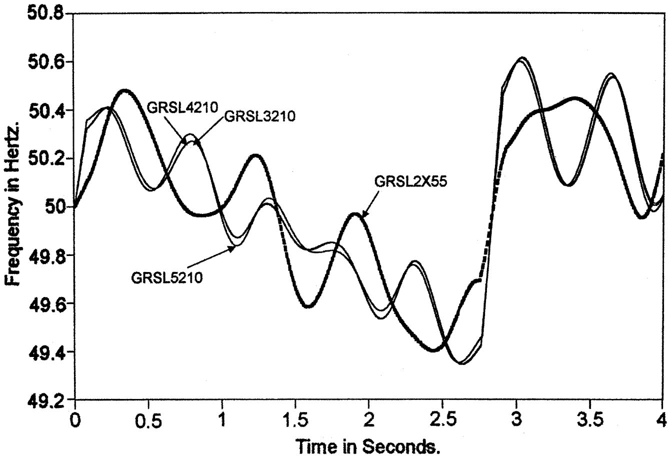

Fig. 8. Frequency of some machines in island-3.

C. Implementation of Islanding

The number of intersection lines among the five prespecified sections (mentioned in Table I) of the BPDB system is five. It is being proposed that these intersection lines be monitored constantly in real time by installing microprocessors at the substa-

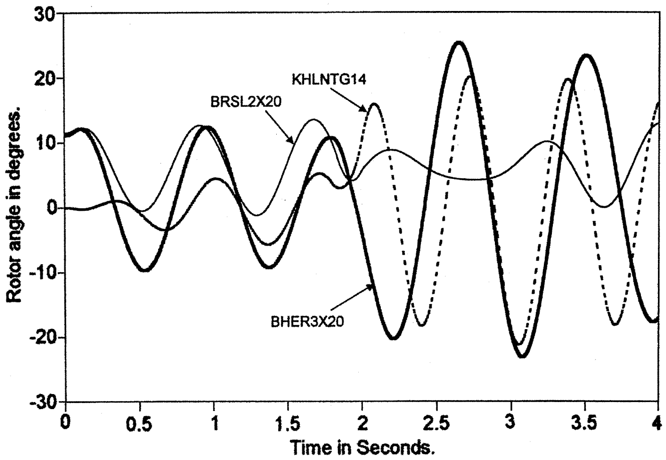

Fig. 9. Oscillations of some machines in island-4 relative to KHLNBMPP machine for fault clearing with five islands.

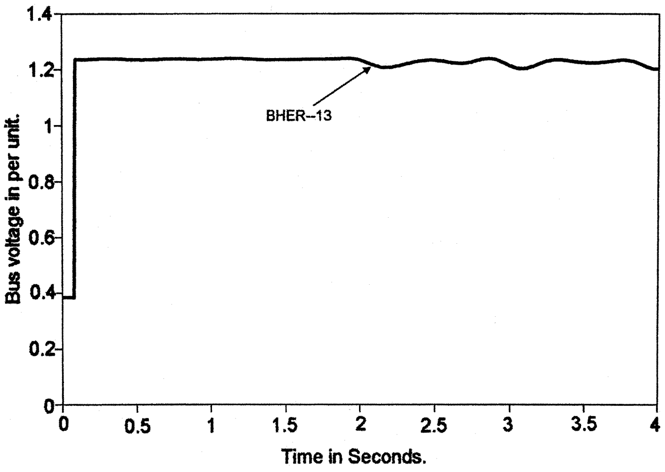

Fig. 10. Voltage at the bus BHER—13 in island 4.

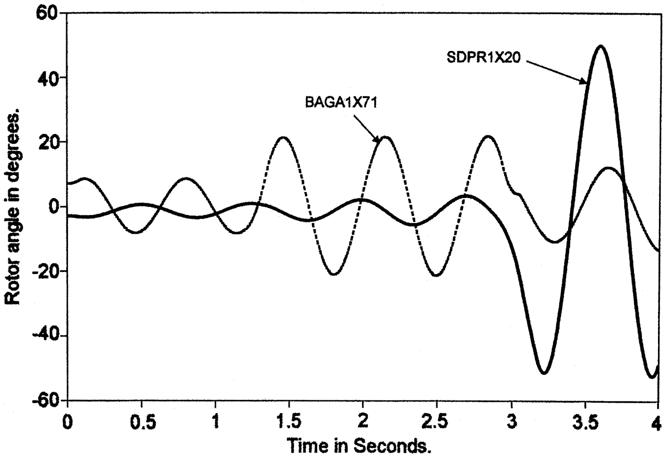

Fig. 11. Oscillations of some machines in island-5 relative to RANGX20 machine for the case of fault clearing with five islands.

tions at both ends of the respective lines. These microprocessors will record the megawatt (active-power) flow in each line at a convenient sampling rate [13] e.g., 1 kHz. If the difference between the recorded flow values for two consecutive instants of time t_1 and t_2 exceeds a threshold at both ends of an intersection line, then this line will be tripped for islanding the system. This approach is used because exceeding the set threshold value can be considered as a possibility of a fault occurrence that requires such islanding. However, to make sure that the changes in line megawatt flow do not correspond to a transient disturbance, the microprocessor will provide the decision on line tripping after a delay for a suitable interval of time. Since the stability analysis for the crucial fault (blackout) has revealed that clearing a fault through islanding in 0.08 s (i.e., four cycles) can prevent a blackout in the BPDB system, the delay time can be set as 1.5 cycles (i.e., 0.03 s) so that the remaining 0.05 s (i.e., 2.5 cycles) will be enough for the operation of the line breakers in the BPDB system.

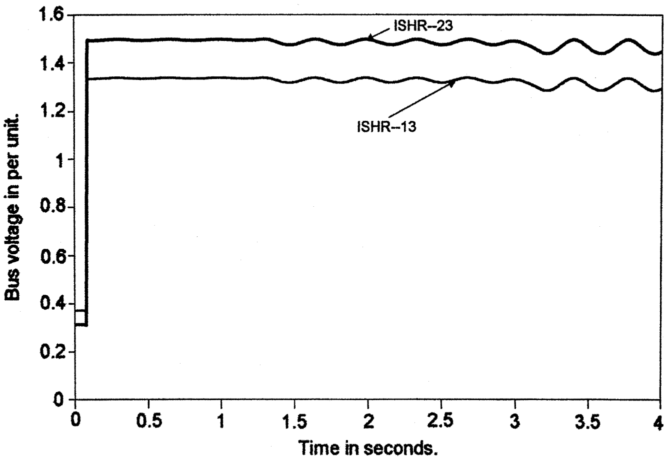

Fig. 12. Voltage at some of the buses in island-5.

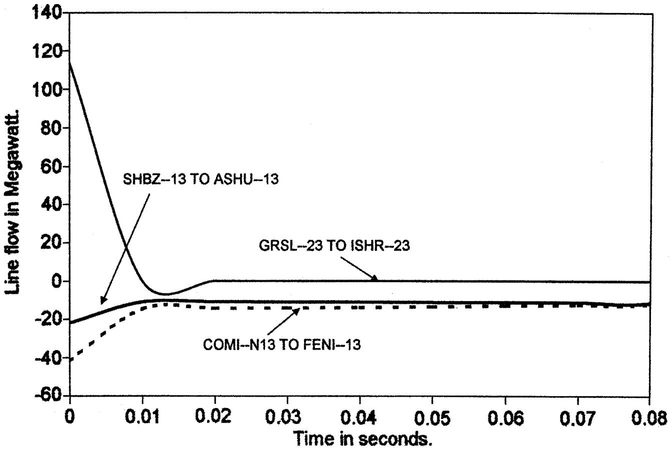

Fig. 13. Real power (megawatt) flows in some of the transmission lines in the East zone before clearing the fault of June 20, 1998.

To propose a threshold percentage appropriate for the BPDB system, the present work has determined the line active-power (megawatt) flows in the lines existing between five sections of the BPDB system under the blackout case. In addition to this, five more assumed fault cases have also been studied separately in a similar manner. Each of the assumed fault cases is considered as occurring on an internal line of the corresponding section under the same prefault scenario (i.e., the peak operating condition existing at 19:00 h of June 20, 1998). As representative cases, the megawatt flows in the five intersection lines for a time span from $t = 0$ to 0.08 s for the blackout and one of the assumed five fault cases have been shown in Figs. 13–16.

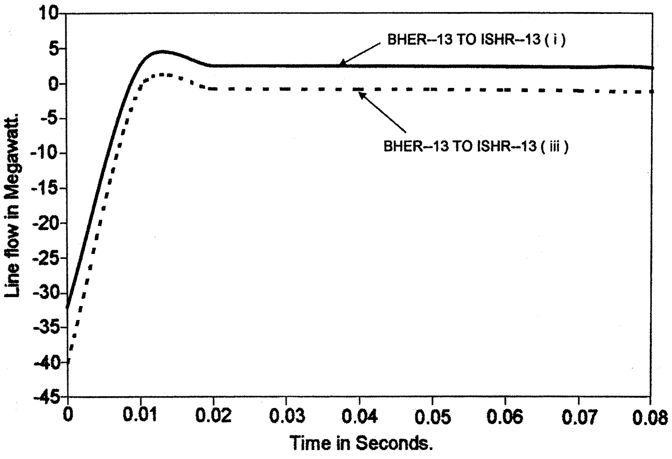

Fig. 14. Real-power (megawatt) flows in some of the transmission lines in the West zone before clearing the fault of 20th June 1998.

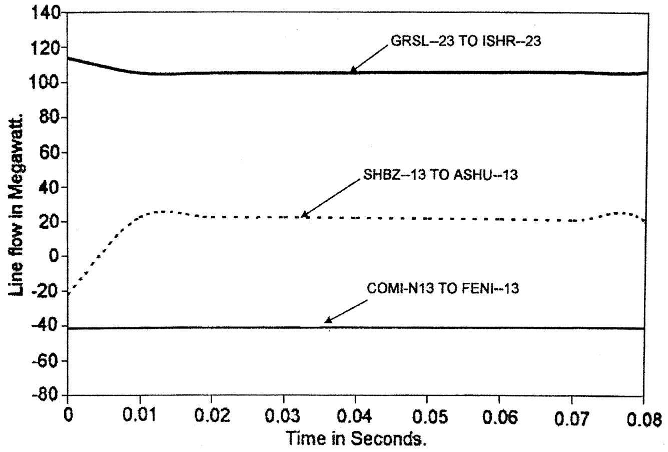

Fig. 15. Real-power (megawatt) flows in some of the transmission lines in the East zone before clearing a fault assumed in one circuit of the line FENPS-13 to SYLH-13.

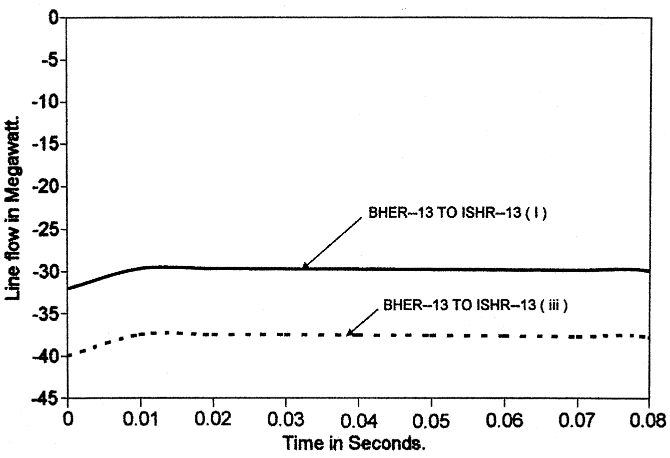

Fig. 16. Real-power (megawatt) flows in some of the transmission lines in the West zone before clearing a fault assumed in one circuit of the line FENPS-13 to SYLH-13.

An inspection of all such profiles for all of the intersection lines between two instants $t_1 = 0$ and $t_2 = 0.01$ s have revealed that the threshold may be set as 15%.

The number of islands to be formed for a fault will depend upon the number of intersection lines in which the change in line flow between two sampling instants exceeds the set threshold. It should be noted that if for a fault case the active-power flow changes in all the specified five intersection lines are 15% or less, then the system will not be islanded for that fault case. So upon implementing the proposed scheme, a fault occurring in the BPDB system will result in two to five islands or none.

It is noteworthy that an alternative to islanding is keeping the system intact where possible and resorting to load/generation shedding. Studies on this alternative option have also been made for each of the five assumed fault cases. These studies have revealed that mere load/generation shedding without islanding cannot avert blackout in the BPDB system for any fault case that causes more than 15% change in megawatt flow in an intersection line between two sampling instants.

D. Implementation of Load and Generation Switching to Supplement Islanding

There are two points to be considered: 1) how much generation shed and/or load shed/injection is needed and 2) how to realize these sheds or injections immediately after fault clearing through islanding. It is being proposed that to determine the amount and location of generation shed and load switching, transient stability studies can be made by the National Control Center. These studies will be performed in advance as part of security analysis [14] for different cases and faults in the system, each with various numbers of islands under the same peak operating condition. The results obtained can be transferred to the computers of each area (section) control center. As soon as the grid system is islanded, the area control center will transmit signals to respective grid substations and generating unit control rooms to shed or inject load and/or decrease generation in proportions near the values already obtained from security analysis. It should be noted that the decisions on load/generation shed or injection corresponding to peak-hours' operating condition usually act as guidelines for offpeak hours' operating conditions when the system is less constrained.

V. CONCLUSIONS

This paper has proposed an islanding scheme to avert a blackout in real time after a fault occurs. This has been tested through comprehensive simulations on a practical and vulnerable power system, namely the BPDB system. The following are the main conclusions of the work presented here.

i) Whether any fault warrants islanding the BPDB system can be decided through real-time digital monitoring of the megawatt flows in each of the lines between a number of prespecified sections. An intersection line will be tripped due to a fault if the megawatt flow changes between two successive sampling instants by more than a threshold percentage at both ends of the line or else it will remain intact. This will result in splitting the system into two or more islands or none at all depending upon the severity and location of the fault.

ii) The threshold percentage for the BPDB system has been proposed as 15% through comprehensive studies on the intersection line flows for the blackout of June 20, 1998 and five more assumed fault cases under the same prefault and peak operating condition. However, this threshold can always be reviewed from time to time when there are changes in the system topology and generation/demand growth. Moreover, in the course of time, if wide differences between the peak and offpeak operating conditions of the system arise, a separate threshold may also be contemplated for faults occurring during offpeak hours.

iii) It has been observed from the extensive simulation studies on the BPDB system that for those faults that have contributed to more than 15% changes (between two consecutive sampling instants) in the megawatt flow of any intersection line, a blackout cannot be averted by only load/generation shedding while keeping the system fully connected (i.e., no islanding).

iv) Alongside islanding, there is a need for shedding some megawatt/mega volt ampere reactive (MVAR) generation and/or load at various locations to maintain the stability of the synchronous machines operating in the respective islands. It is proposed that the guidelines in determining the amounts and locations of generation shedding and load switching in each island be obtained from an array of transient stability studies, made as part of the security analysis.

The underlying philosophy of the proposed scheme of islanding may also be implemented in other power systems using existing hierarchies of computerized control.

REFERENCES

[1] M. M. Rahman and N. G. Saha, “System reliability of Bangladesh power system,” in Proc. Int. Symp. Elect. Energy Syst., Dhaka, Bangladesh, 1993.

[2] N. Grudinin and I. Roytelman, “Heading off emergencies in large electric grids,” *IEEE Spectrum*, vol. 34, pp. 43–47, Apr. 1997.

[3] Y. Hain and I. Schweitzer, “Analysis of the power blackout of June 8, 1995 in the Israel electric corporation,” *IEEE Trans. Power Syst.*, vol. 12, pp. 1752–1758, Nov. 1997.

[4] V. Vittal, W. Kliemann, Y. -X. Ni, D. G. Chapman, A. D. Silk, and D. J. Sobajic, “Determination of generator groupings for an islanding scheme in the Manitoba hydro system using the method of normal forms,” *IEEE Trans. Power Syst.*, vol. 13, pp. 1345–1351, Nov. 1998.

[5] M. Thaden, “Analysis of a major load island outage on the Potomac electric power company system,” *IEEE Trans. Power Syst.*, vol. 14, pp. 306–311, Feb. 1999.

[6] C. W. Taylor, “Improving grid behavior,” *IEEE Spectrum*, vol. 36, pp. 40–44, June 1999.

[7] M. A. Pai, *Computer Techniques in Power System Analysis*. Tata, New Delhi: Tata McGraw-Hill, 1979.

[8] M. Anderson and A. A. Fouad, *Power System Control and Stability*. Ames, IA: Iowa State Univ. Press, 1977, vol. I.

[9] J. Arrilaga, C. P. Arnold, and B. J. Harker, *Computer Modeling of Electrical Power Systems*. New York: Wiley, 1983.

[10] W. D. Stevenson Jr, *Elements of Power System Analysis*. New York: McGraw-Hill, 1982.

[11] K. Zollenkopf, “Bifactorization– Basic computational algorithm and programming techniques,” in *Proc. 1970 Conf. on Large Sets of Linear Equations*, Oxford, U.K., pp. 75–96.

[12] E. W. Kimbark, *Power System Stability*. New York: Wiley, 1961, vol. I.

[13] H. Ungrad, W. Winkler, and A. Wiszniewski, *Protection Techniques in Electrical Energy Systems*. New York: Marcel Dekker Inc., 1995.

[14] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation and Control*. New York: Wiley, 1996.

S. Shahnawaz Ahmed (M’85—SM’94) received the B.Sc. and M.Sc. degrees from Bangladesh University of Engineering and Technology (BUET), Dhaka, and the Ph.D. degree in electrical engineering from the University of Manchester Institute of Science and Technology, Manchester, U.K., in 1987.

Currently he is a Professor of the Faculty of Electrical Engineering at Universiti Teknologi Malaysia (UTM), Skudai, and on leave from BUET until March 2003. Since 1983, he has been with BUET where he became a full Professor in 1996. He has authored many publications and has served as a reviewer for a number of international journals including IEE Proceedings and IEEE Transactions. His research interests include modeling, simulation and real-time control of power systems, FACTS, SMES, and photovoltaic arrays.

Narayan Chandra Sarker (M’96) received the B.Sc. and M.Sc. degrees in electrical engineering from Bangladesh University of Engineering and Technology, Dhaka, in 1980 and 1999, respectively.

Currently, he is with the Bangladesh Power Development Board, where he has been for the last 21 years, accumulating vast experience in operation, control and instrumentation, and maintenance of thermal power stations.

Azhar B Khairuddin received the B.Sc.degree in electrical engineering from Louisiana State University, Baton Rouge, in 1985, and the M.Sc. degree in electrical engineering from Universiti Teknologi Malaysia (UTM), Skudai, in 1992.

Currently, he is a Senior Lecturer in the Faculty of Electrical Engineering at UTM. He is the author of many papers. His research interest is in power system operation and analysis.

Mohd Ruddin B Abd Ghani (M’90) received the B.E.E. (Hons.) degree from Universiti Teknologi Malaysia (UTM) in 1977, and the Ph.D. degree in systems engineering and control from the University of Manchester Institute of Science and Technology, Manchester, U.K., in 1989.

Currently he is on deputation from UTM and serving as the Rector of the National Technical University College, Melacca, Malaysia. He is a Professor of the Faculty of Electrical Engineering at UTM. His current work and research interests include dynamic economic dispatch and unit commitment, distribution automation, optimization of large-scale systems, expert system applications, and advanced control techniques applications in power systems. He has published and presented many papers and articles.

He is a committee member of the Malaysia National International Electrotechnical Commission (IEC).

Hussein Ahmad (M’87—SM’95) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Strathclyde, Glasgow, Scotland, in 1977 and 1981, respectively, and the Ph.D. degree from the University of Manchester Institute of Science and Technology, Manchester, U.K., in 1986.

Currently, he is with Universiti Teknologi Malaysia, Skudai, where he became Full Professor in 1997. His research areas include power system operation, HV insulation and dielectrics, and lightning protection. He is also an HV installation and lightning protection consultant to numerous organizations in the energy and telecom sector of Malaysia. He has published and presented many papers.

Dr. Ahmad is a member of CIGRE.