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An Optimal Control Strategy for Multi-Terminal HVDC Systems

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ABSTRACT. An optimal control strategy for the modulation of the DC power of multiterminal HVDC Systems is proposed. The modulated DC power is utilized to enhance the operation of AC systems. The linear programming optimization method along with the feasible direction algorithm was used to obtain the optimum DC current settings. The control strategy has been tested on two hypothetical multi-terminal HVDC systems. The proposed strategy proves to be effective in improving the system response. Another characteristic of this scheme is that improvements of one machine will not be at the expense of other machines. The control scheme will enhance the transient stability if there is a room in the power system to enhance.

KEYWORDS: HVDC systems, Optimal Control, Stability

1. Introduction

The potential of utilizing an HVDC system to enhance the performance of an AC system is well known and documented[1-7]. Several models have been proposed for the simulation of AC/DC systems in transient stability studies. This paper deals with use of the optimization techniques for the control of Multi-Terminals DC (MTDC) systems. Optimization techniques have been applied for the control of HVDC systems. For example, Hamzei proposed a systematic method that is based on the linear programming formulation[8]. It is used to find the DC network solution of a general multi-terminal HVDC system and it's mode of operation. The objective function is to minimize the sum of the cosine function of the control angles. The constraints are the network equations, the control angles and the current orders.

Another area where optimization techniques were applied is correcting the voltages in AC-HVDC systems. The problem was formulated as a linear programming model. The objective function is to minimize the absolute values of the corrections to be made. The constraints are the system voltage and current equations. They also include the power change at the generator buses and the transmission line ratings.

Hamzei and Ong have proposed a model to coordinate the injections of a multi-terminal DC system[9]. The objective function was to minimize the active power changes.

This paper reports on the use of the feasible direction algorithm to determine the optimal setting of the HVDC system. Section two introduces the optimization model and the method of solution. The model implementation is described in section three. The simulation results and discussion are presented in section four. Conclusions are drawn in section five.

2. The Optimization Model

The feasible direction method is employed to find the best setting of the HVDC side to stabilize the AC system. The method generates an improving feasible direction. It also determines a step size in that direction.

2.1 *Feasible Direction Algorithm*

The class of *Feasible Directions Methods* solves a non-linear programming problem by moving from a feasible point to an improved feasible point[10-11]. That is, given a feasible point x_k, a direction d_k is determined such that for $\lambda > 0$ and sufficiently small, the following two (2) properties are true:

1. $x_k + \lambda\ d_k$ is feasible, and

2.The objective function at $x_k + \lambda\ d_k$ has a better value than at x_k.

Where d_k direction along which the variable x_k improves

The method of feasible direction involves two steps. The first step is the direction generation. In the second step, the step size is determined. These two steps are explained below.

2.1.1 *Generating Improving Feasible Directions*

Given a feasible point x_k, a nonzero vector d_k is a feasible improving direction if $\nabla f(x_k)^t d_k > 0$, and d_k satisfies the set of constraints. The feasible set is determined by a set of linear inequalities and equations given as $A_1 d \leq 0$, and Ed=0. The improving direction is generated by minimizing $\nabla f(x_k)^t d_k$ subject to the constraints $A_1 d_k \leq 0$ and $Ed_k=0$. This problem is formulated as follows:

Minimize $$\nabla f(x_k)^t d_k \tag{2.1}$$

Subject to $$A_1 d_k \leq 0 \tag{2.2}$$

$$Ed_k = 0 \tag{2.3}$$

where A_1 and E are linearized matrices of the original nonlinear problem. They represent the coefficient of the inequality and equality constraints.

2.1.2 *Step Size Generation*

Given that direction generated in the previous step, the next step is to determine the step size in the direction d_k. The bounding interval algorithm is used to determine the range for λ. The Golden Search then is employed to find the optimal λ_k^*. These steps are given below.

Step 1: Find the interval [a, b] where λ lies, using Interval Bounding algorithm.

Step 2: Use Golden Search Method to obtain λ_k^*

Step 3: The new solution will be:

$$x_k = x_k + \lambda_k^* \, d_k \tag{2.4}$$

where λ_k^* is the optimal value λ.

The feasible direction method is terminated when $\|d_k\| \leq \varepsilon$.

3. Implementation of the Feasible Direction Method

High Voltage DC Transmission systems are known to have the ability to change their transmitted power. This inherent feature of the HVDC systems is utilized for the support of the ac systems in case a transient event occurs. The HVDC system helps to reduce the accelerating power of machines following a fault. The rate and level of the increase in the HVDC power, in response to the ac system needs, is achieved through many techniques. This section presents the development of an optimization model to determine the level of dc power.

In order to build up an appropriate optimization model, the AC-HVDC objective function and constraints are defined. An objective function may be formed to minimize the accelerating power of the machine. The objective function is stated as follows:

$$\text{Min } Z = \sum_{i=1}^{N} (P_{mi} - P_{ei})^2 \qquad (2.5)$$

N: number of the electrical machines
P_{ei}: Electrical output power of the i-th machine
P_{mi} Mechanical input power of the i-th machine

The model constraints are the AC and the HVDC equations. They are solved through Newton-Raphson method. The network constraints have the form given in equation 2.6

$$R_{ac/dc} = - J_{ac/dc} \, \Delta X_{ac/dc} \qquad (2.6)$$

where:
$R_{ac/dc}$: a column vector of the ac/dc residuals.
$J_{ac/dc}$: The Jacobian matrix of the ac/dc network
$\Delta X_{ac/dc}$: a column vector of the changes of the ac/dc variables

The intention is to link the HVDC constraints to the objective function of equation 2.5. Hence equation 2.6 can be rewritten as:

$$R'_{dc} = - J_{dc} \, (\Delta X_{dc} + \Delta X_{aux}) \qquad (2.7)$$

where:

R'_{dc} : column vector of the dc residuals.

J_{dc} : a Jacobian matrix of the dc variables.

ΔX_{dc}: a column vector of the changes of the dc variables

ΔX_{aux}: a column vectors of the changes in auxiliary variables

Let ΔX_{aux} be equal to λd then equation 2.7 becomes:

$$R_{dc}' = - J_{dc} \ (\Delta X_{dc} + \lambda d) \qquad (2.8)$$

The residuals cannot be zero, otherwise a trivial solution is obtained. The residuals are set to small values in order to provide nonzero solution for the direction vector (d).

The vector ΔX_{aux} represents the constraints to the objective function. The Gradient method can be applied to solve this problem. The model becomes as shown in equation 2.9.

$$\text{Min } Z = \sum_{i=1}^{N} (P_{mi} - P_{ei})^2 \qquad (2.9)$$

subject to:

$$R_{dc}' = - J_{dc} \ \Delta X_{aux} \qquad (2.10)$$

or

$$R_{dc}' = - J_{dc} \ \lambda d \qquad (2.11)$$

Z is the above objective function to be minimized.

The function, $\Delta f(y)$, represents the change in the accelerating power in response to the control variables. It can be numerically calculated and is equal to $-2(P_{mi} - P_{ei}) * \frac{\partial P_{ei}}{\partial X}$.

Equations 2.7 and 2.9 form the required optimization model. It has a linear form and is solved by using the Golden Search Method. It is worth noting that the objective function is not a direct function of the DC variables. It is, however, a function of the AC variables.

4. Results and Discussion

This section describes the results of the implementation of the optimization model when applied to two MTDC power systems. The studies include the assessment of the system performance following a three-phase fault at a major busbar. The evaluation consists of the system response due to:

a. No DC power control i.e. the DC power is not modulated or controlled.
b. Applying a modulating signal to increase the DC power in an arbitrary manner. This is referred to as Control Scheme I.
c. Applying the optimization algorithm without using the Golden Search Technique to determine λ . This assumes that $\lambda = 1.0$. This is referred to as Control Scheme II.
d. Applying the optimization algorithm using Golden Search Technique. This is referred to as Control Scheme III.

An HVDC link is capable of changing the transmitted power, within its rating, in a fast manner. This flexibility in control can vary the transmitted power in accordance to the AC system needs. The power can be modulated in response to any of several signals. These signals give indications of the state of the AC systems. The signals can be:

(a) Speed deviation from synchronous speed, $\Delta\omega$
(b) Rotor slip
(c) Change in generator power
(d) Change in tie-line power
(e) A combination of the above.

The signals are applied through controller of various transfer functions. However, only a simple time-lag controller is used in this paper. The output of the controller is the required change in the DC current. The latter is used to determine the required DC power.

4.1 20-*Bus System Study*

A 20-bus system, whose single line diagram is shown in Fig.1, has been selected for the study. The network belongs to a Middle Eastern utility. It has inherent stability problems. The power system is an AC network. However for the purpose of this study a three terminals MTDC system is proposed. The system data is given in Appendix A1.

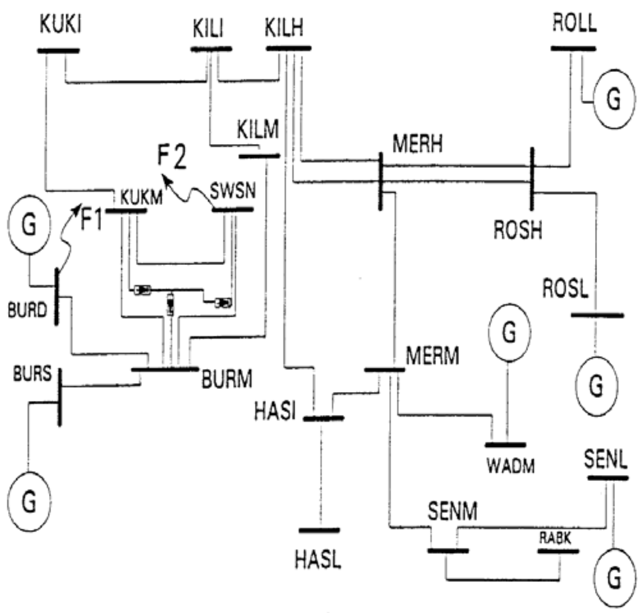

FIG. 1. A20-Bus Test System.

The transient behavior of the system will be investigated for two fault locations. The first location is near a generator while the second is close to an inverter terminal.

The response of the rotor angle of machine at ROLL is shown following a 3-phase fault at the generator Bus of BURD. The fault duration is 100 milliseconds. Figure 2 shows the variations of the rotor angle of the machine under the various control schemes. Three signals are applied separately to the controller. These signals are rotor slip, generator power and electric power-mechanical difference signals. Control Scheme II uses the linear optimization model derived in section 2. In this scheme λ is assumed to be equal to unity. Control Scheme III uses the Golden Search Method. Golden Search will seek for the optimum λ^*. This, of course, will require freezing the time and iteration to find λ^*. Figure 2 shows the system performance under the three control schemes. Control schemes II & I tend to overdamp the generators slightly as compared with no control scheme. Control Scheme III improves the behavior slightly.

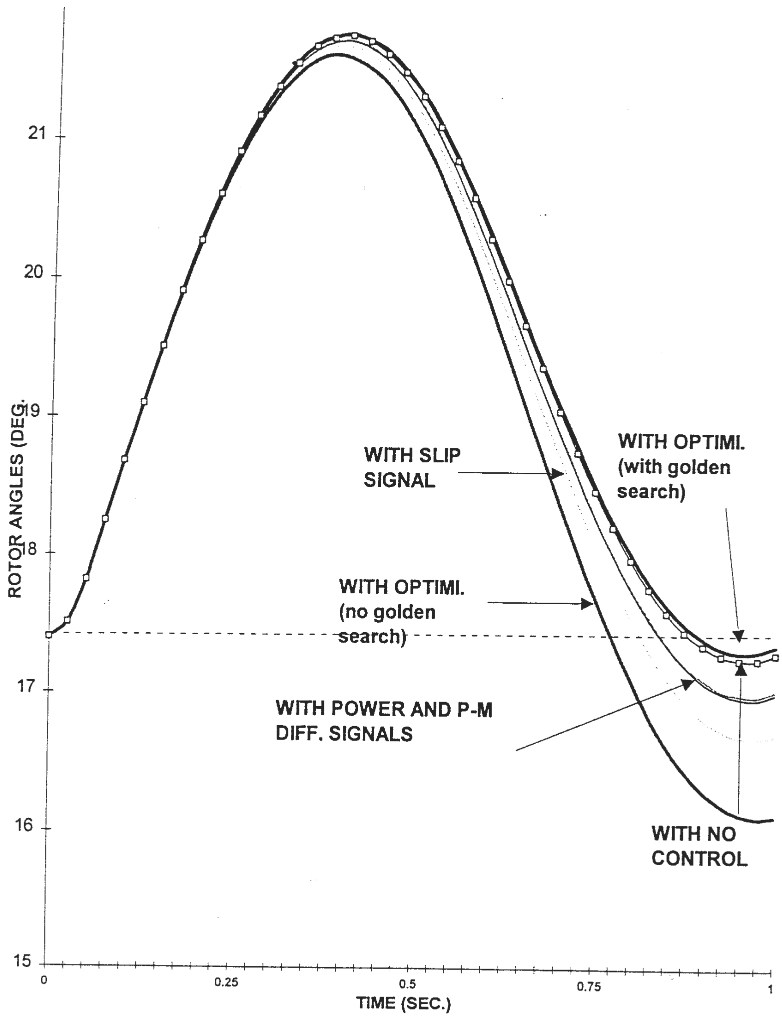

FIG. 2. Rotor Angle at ROLL due to Fault No.1 with various Control Strategies.

Figure 3 shows the angular variations of the machine at WADM if the fault location is changed to SWSN which is near the inverter terminal. The fault duration is 0.1 sec. The machine may lose synchronism if the DC power is controlled without the Golden Search technique. The response is much better when the DC power is controlled through the optimization algorithm. This shows that increasing the DC power in arbitrary manner may cause instability in some systems.

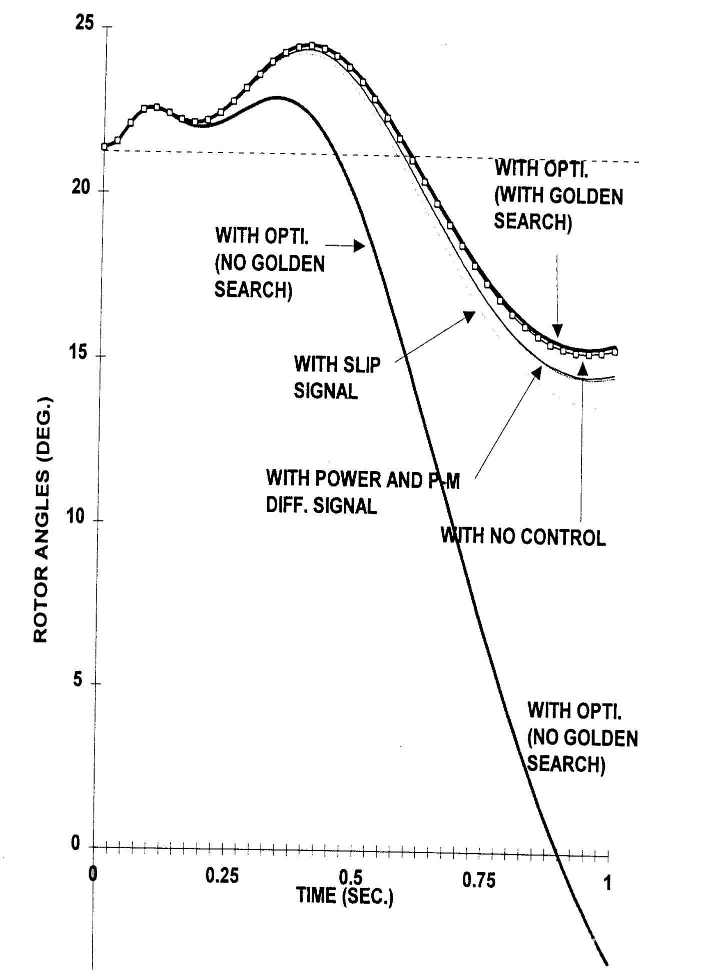

FIG. 3. Rotor Angle at WADM due to Fault No.2 with various Control Strategies.

4.2 24-*Bus System Study*

The second study system is a 24-bus, 5- machines network. A Three-terminals HVDC system has been proposed. Two faults have been selected, F1 is close inverter no.1 and F2 is on bus03. Figure 4 shows the single line diagram of the study network. The system data is given in Appendix A2. The rotor angle variation of generator bus04 is shown in Figure 5. The generator is shown to lose stability as a result of the system fault. Both control schemes II and I fail to stabilize the machine. Scheme II is closer to succeed. Only scheme III will stabilize the machine.

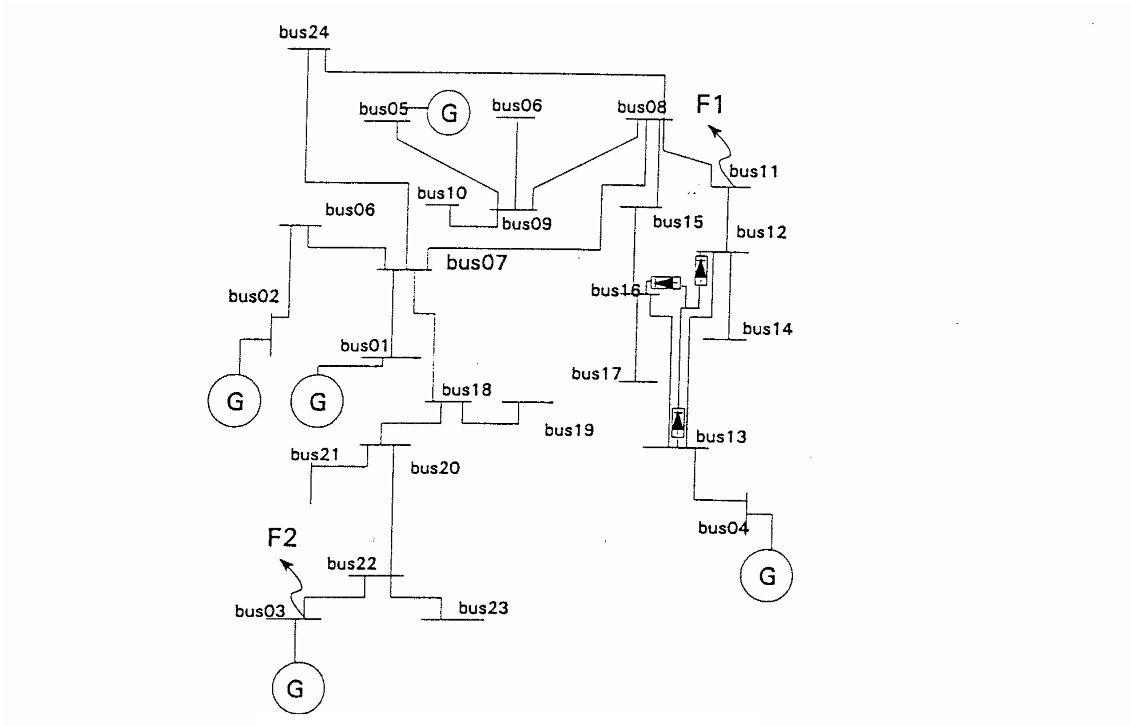

FIG. 4. A-24 Bus Test System.

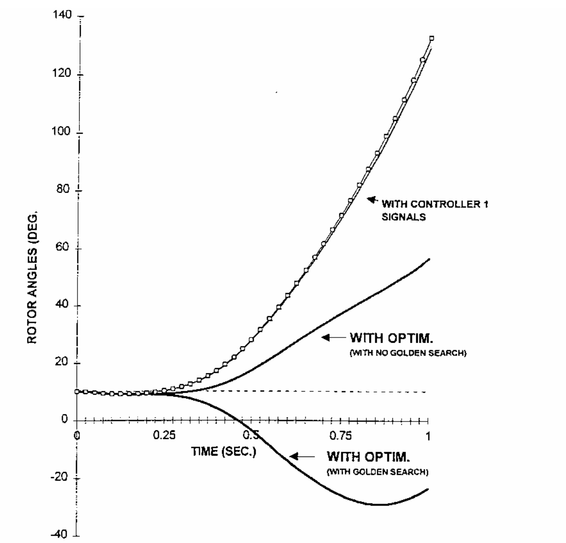

FIG. 5. Rotor Angle of generator at bus04 due to Fault 1with Various Control Schemes.

Figure 6 shows the voltage variations at busbar bus04 following the fault under the various control schemes. The busbar voltage experiences a severe dip to 0.92 p.u. when the control scheme III is adopted. This scheme requires that the generator at bus04 should supply a large amount of power in order to stabilize the entire system. Consequently, the machine terminal voltage experiences such a dip.

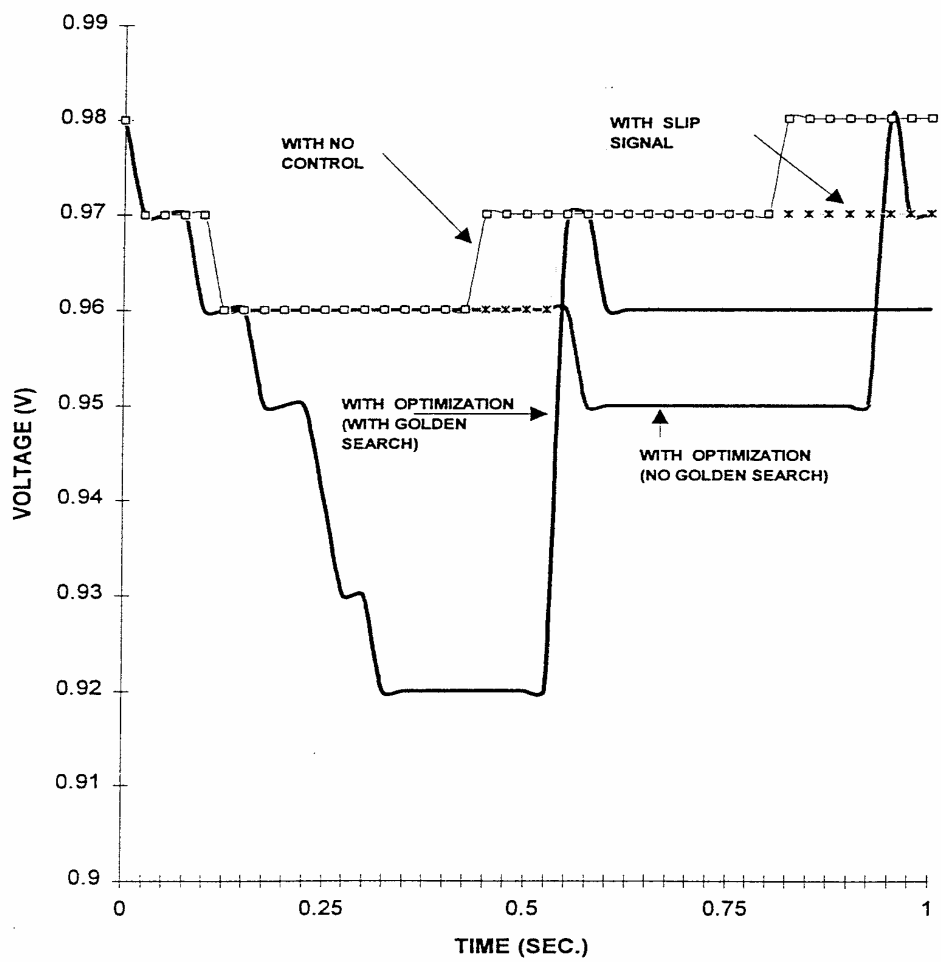

FIG. 6. Voltage Profile at bus04 with various Control Strategies.

Another three-phase fault (F2) was applied on bus03 for 50 ms. the rotor angles response of generator bus04 is shown in Figure 7. The generator loses synchronism due to the fault. Neither of the schemes is able to stabilize the machine. The HVDC link is far from the fault location and thus its impact is negligible.

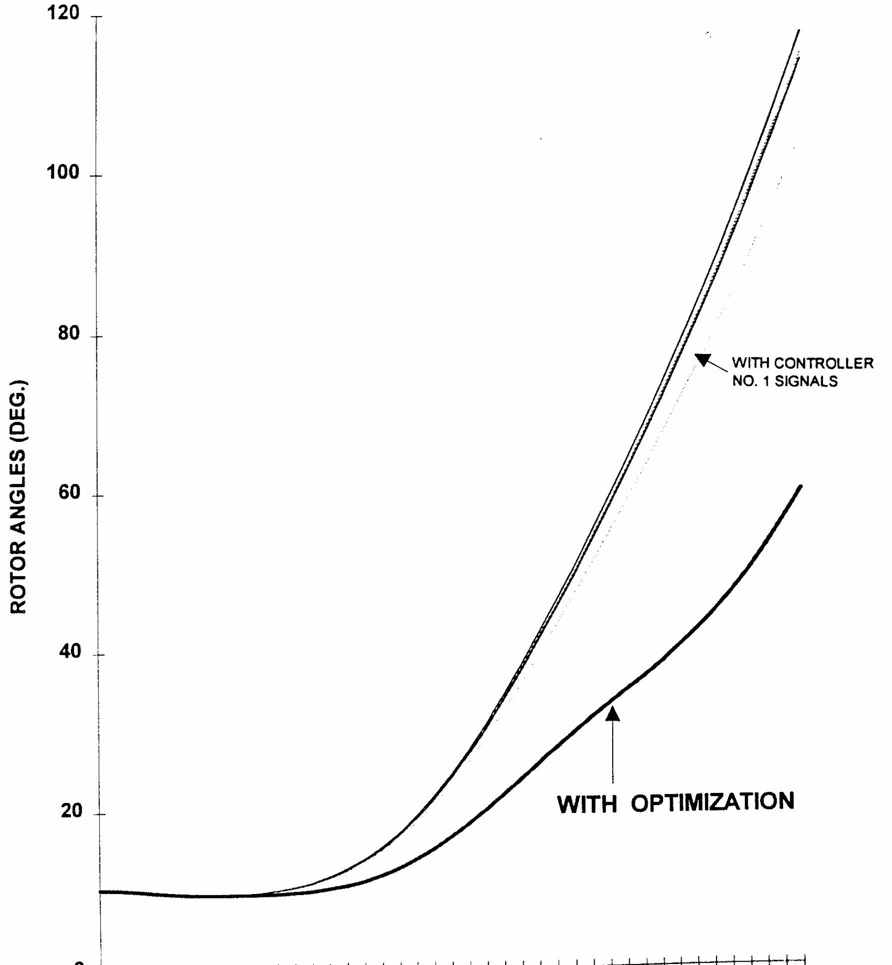

FIG. 7 Rotor Angle of generator at bus04 due to Fault 2 with various Control Schemes.

5. Conclusion

In this paper, three main control schemes have been applied to improve the AC transient stability through HVDC systems. These control schemes were applied to two multimachine systems, on which two three phase faults were applied. The Linear Programming optimization method along with the feasible direction concept proves to be effective in improving the system response. One other characteristic of this scheme over the rest is that an improvement of one machine will not be at the expense of other machines. It shall be noted that the location, duration, type of fault and the power system configuration will affect the contribution of the applied control scheme and the HVDC system. The control scheme will enhance the transient stability if there is room in the power system to enhance. Enhancement cannot be brought from outside the system but from inside by properly and quickly changing the parameters of the MTDC system in the AC power systems.

Notations

x_k	Feasible point
d_k	Direction along which the variable x_k improves.
λ	constant to speedup the improvement in the variable x_k .
λ_k^*	The optimal value of λ
N:	Number of the electrical machines
P_{ei}:	Electrical output power of the i-th machine
P_{mi}	Mechanical input power of the i-th machine
$R_{ac/dc}$	A column vector of the ac/dc residuals.
$J_{ac/dc}$	The Jacobian matrix of the ac/dc network
$\Delta X_{ac/dc}$	A column vector of the changes of the ac/dc variables
R'_{dc} :	Column vector of the dc residuals.
J_{dc}	A Jacobian matrix of the dc variables.
ΔX_{dc}	A column vector of the changes of the dc variables
ΔX_{aux}	A column vector of the changes in auxiliary variables

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Appendix A1
20-Bus System Data

Busbar Data

Bus No.	Bus Name	Voltage (PU)	Angle (Deg)	PG (MW)	QG (MVAR)	PL (MW)	QL (MVAR)
1	BURS	1.00	0.00	4.00	0.00	0.00	0.00
2	BURD	1.00	0.00	2.00	0.00	0.00	0.00
3	BURM	1.00	0.00	0.00	0.00	13.00	10.00
4	SWSN	1.00	0.00	0.00	0.00	20.00	20.00
5	KILM	1.00	0.00	0.00	8.00	6.00	0.00
6	KUKM	1.00	0.00	0.00	0.00	12.00	10.00
7	KUKI	1.00	0.00	0.00	0.00	0.00	0.00
8	KILH	1.00	0.00	0.00	0.00	0.00	15.00
9	KILI	1.00	0.00	0.00	0.00	0.00	0.00
10	MERH	1.00	0.00	0.00	0.00	0.00	15.00
11	ROSH	1.00	0.00	0.00	0.00	0.00	0.00
12	ROSL	1.05	0.00	22.00	0.00	0.00	0.00
13	ROLL	1.04	0.00	47.40	0.00	0.00	40.00
14	HASI	1.00	0.00	0.00	0.00	0.00	0.00
15	HASL	1.00	0.00	0.00	0.00	6.00	4.00
16	MERM	1.00	0.00	0.00	0.00	0.00	0.00
17	WADM	1.03	0.00	3.00	0.00	7.00	5.00
18	SENM	1.00	0.00	0.00	0.00	0.00	0.00
19	RABK	1.00	0.00	0.00	0.00	3.00	2.00
20	SENL	1.00	0.00	12.00	0.00	12.00	8.00

Machine Parameters

Bus	Gen. MVA	Inertia constant H (sec)	Direct axis transient reactance	Quadrature axis transient reactance	Direct axis synchronous reactance	Quadrature axis synchronous reactance
ROSL	33.50	4.50	0.28	0.40	0.77	0.40
ROLL	33.50	9.00	0.14	0.20	0.39	0.20
SENL	9.90	4.44	0.15	0.30	0.51	0.30
BURS	12.50	10.20	0.07	0.67	0.67	0.67
BURD	3.75	5.50	0.07	0.37	0.31	0.37
WADM	3.39	2.10	0.14	0.41	0.73	0.41

HVDC Parameters

Terminals

Rectifier	Inverter	Inverter
KUKM	SWSN	BURM

Line Data

FROM	TO	Resistance (PU).	Reactance (PU)	SUSC. (PU)	Tap(%)
BURS	BURS	0.00	0.384	0	0
BURD	BURM	0.00	0.213	0	0
BURM	KILM	0.21	0.358	0	0
BURM	KUKM	0.04	4.9	0	0
SWSN	KUKM	0.02	4.9	0	0
BURM	SWSN	0.04	0.029	0	0
KUKM	KUKI	0.00	0.116	0	-5.0
KUKI	KILI	0.0047	0.0233	0.010	0
KILI	KILM	0.00	0.4025	0	-5.0
KILH	KILI	0.00	0.07	0	-2.0
MERH	KILM	0.02	0.14	0.2362	0
MERH	KILM	0.02	0.14	0.2362	0
ROSH	MERH	0.04	0.26	0.432	0
ROSH	MERH	0.04	0.26	0.432	0
ROSH	ROLL		0.1485	0	0
ROSH	ROSL		0.297	0	0
MERH	MERM		0.156	0	0
MERH	HASI	0.14	0.186	0.0175	
KILI	HASI	0.307	0.407	0.038	0
HASI	HASL	0	0.636	0	-4.0
MERM	WADM		1.265	0	-2.0
MERM	SENM	0.2505	0.333	0.0312	0
SENM	RABK	0.289	0.378	0.0354	0
SENM	SENL	0	1.1		0
KUKM	KUKM		-40		
SWSN	SWSN		-40		
BURM	BURM		-40		

Specified DC Power

PDC (REC.) (MW)	PDC (INV.1) (MW)	PDC (INV.2) (MW)
28.7	21	7.7

Initial Firing Angles (Deg)

Rectifier	Inverter	Inverter
5.00	5.00	5.00

Appendix A2

24-Bus System Data

Busbar Data

Bus No.	Bus Name	Voltage (PU)	Angle (Deg)	PG (MW)	QG (MVAR)	PL (MW)	QL (MVAR)
1	bus01	1.00	0.00	78.00	40.00	0.00	0.00
2	bus02	1.00	0.00	100.00	20.00	0.00	0.00
3	bus03	0.99	0.00	25.00	8.9	0.00	0.00
4	bus04	0.96	0.00	76.00	42.00	0.00	0.00
5	bus05	1.05	0.00	0.00	0.00	0.00	0.00
6	bus06	1.00	0.00	0.00	0.00	0.00	0.00
7	bus07	1.00	0.00	0.00	0.00	0.00	0.00
8	bus08	1.00	0.00	0.00	0.00	104.99	52.00
9	bus09	1.00	0.00	0.00	0.00	0.00	0.00
10	bus10	1.00	0.00	0.00	0.00	18.00	14.00
11	bus11	1.00	0.00	0.00	0.00	0.00	0.00
12	bus12	1.00	0.00	0.00	0.00	0.00	0.00
13	bus13	1.00	0.00	0.00	0.00	61.00	32.00
14	bus14	1.00	0.00	0.00	0.00	0.00	0.00
15	bus15	1.00	0.00	0.00	0.00	6.00	4.00
16	bus16	1.00	0.00	0.00	0.00	0.00	0.00
17	bus17	1.00	0.00	0.00	0.00	0.00	0.00
18	bus18	1.00	0.00	0.00	0.00	0.00	0.00
19	bus19	1.00	0.00	0.00	0.00	51.00	10.00
20	bus20	1.00	0.00	0.00	0.00	0.00	0.00
21	bus21	1.00	0.00	0.00	0.00	12.00	6.00
22	bus22	1.00	0.00	0.00	0.00	0.00	0.00
23	bus23	1.00	0.00	0.00	0.00	28.00	10.00
24	bus24	1.00	0.00	0.00	0.00	0.00	0.00

Machine Parameters

Bus	Gen. MVA	Inertia constant H (sec)	Direct axis transient reactance	Quadrature axis transient reactance	Direct axis synchronous reactance	Quadrature axis synchronous reactance
bus01	100	5.08	0.2005	0.2005	1.305	0.85
bus02	100	1.892	0.3235	0.3235	0.9712	0.6325
bus03	100	1.690	0.523	0.523	4.72	4.70
bus04	100	4.400	0.200	0.200	1.970	1.953
bus05	100	0.248	1.55	1.55	5.8	3.75

HVDC Parameters

Terminals

Rectifier	Inverter	Inverter
bus13	bus12	bus16

Specified DC Power

PDC (REC.) (MW)	PDC (INV.1) (MW)	PDC (INV.2) (MW)
18	9	9

Initial Firing Angles (Deg)

Rectifier	Inverter	Inverter
5.00	15.00	15.00

Line Data

FROM	TO	Resistance (PU).	Reactance (PU)	SUSC. (PU)	Tap
bus06	bus02	0.00	0.09	0	10.0
bus06	bus07	0.00476	0.0199	0.01660	
bus07	bus01	0.00	0.1125	0	12.5
bus08	bus24	0.0719	0.3178	0.061	
bus08	bus15	0.0516	0.1062	0.0203	
bus08	bus09	0.00	0.2438	0	-5.0
bus09	bus05	0.00	0.106	0	
bus15	bus16	0.00	0.333		-1.0
bus09	bus10	0.00	0.00629	0	
bus08	bus11	0.0516	0.1062	0.0203	
bus11	bus12	0.00	0.333		-1.0
bus12	bus14	0.00	0.10	0.0	
bus13	bus04	0.00	0.106	0.00	15.0
bus18	bus19	0.00	0.20	0	4.0
bus18	bus20	0.0208	0.0807	0.0754	
bus20	bus21	0.00	0.333		-1.0
bus20	bus22	0.0246	0.0967	0.0777	
bus22	bus23	0.00	0.1667		2.0
bus07	bus08	0.0361	0.145	0.13	
bus07	bus18	0.0148	0.054	0.0536	
bus14	bus14		-20		
bus17	bus17		-20		
bus02	bus02		-40		

استراتيجية تحكم مثلى لأنظمة التيار المستمر متعدد الأطراف

إبراهيم الأمين

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المستخلص : تعتبر الاستقرارية العابـرة جزءًا هامًا فـي تصـميم وتشغيل نظام الطاقة. تتناول هذه الورقة استعمالات أنظمـة التيـار المستمر متعدد الأطراف لتحسين أداء الاستقرارية العابرة لسـرعة تجاوبها في تبديل الطاقة الكهربائية للأنظمة ذات التيار المتردد كأحد المزايا لها. وقد تم عمل نموذج رياضي من أجل تمثيل أنظمة التيار المستمر متعدد الأطراف. وقد تم وضع جميع المعادلات التفاضـلية للنظام وآليات التحكم في البحث على شكل معادلات جبرية ومن ثم حل تلك المعادلات بتطبيق قاعدة المنحرفات. كما تم أيضًـا وضـع نموذج معادلات خطية مثلى وتطبيـق نظريـة البرمجـة الخطيـة كطريقة جديدة للتحكم ودمج هذه الطريقـة مـع نظريـة البحـث الاعتدالي للوصول إلى حل أفضل كطريقة أخرى مقترحة. وأجريت أيضًا دراسة لنوعين من آليات التحكم التقليدية تعمل علـى إشـارة انزلاق دوران المولد الكهربائي وإشارات أخرى لاسـتخدامها فـي التحكم. وتم تطبيق تلك الطرق المقترحة على نظامي طاقة متعددي المولدات حيث أدخل عليها نظام التيـار المسـتمر ذي الأطـراف الثلاثة. وفي النهاية أجريت دراسة مقارنة بين الطـرق المـذكورة وخلصت الدراسة إلى أن استعمال طريقة دمـج نظريـة البرمجـة الخطية مع نظرية البحث الاعتدالي أعطت أفضل النتائج لتحسـين الاستقرارية العابرة لأنظمة التيار المتردد.