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Transient Stability Enhancement Using HPFC Facts Controller

Pallavi Sharma[1], Dr. M. K. Bhaskar[2], Manish Parihar[3], Kapil Parihar[4]

M.E. Scholar, Dept. of EE, MBM University, Jodhpur, Rajasthan, India[1]

Professor, Dept. of EE, MBM University, Jodhpur, Rajasthan, India[2]

Ph.D Scholar, Dept. of EE, MBM University, Jodhpur, Rajasthan, India[3]

Asst. Professor, Dept. of ECE, MBM University, Jodhpur, Rajasthan, India[4]

ABSTRACT:The FACTS controllers have the capability of dynamically controlling the power flow through a line. The considerable price of VSC based FACTS Controllers, such as STATCOM, SSSC, UPFC etc. remains as the major barrier to their widespread use. The existing classical equipment such as switched capacitors, SVC and TCSC have to be replaced, whenever system upgrades or performance improvements are planned. The Hybrid Power Flow Controller (HPFC) uses two equally rated voltage sourced converters to upgrade the functionality of the existing switched capacitors or SVC. This paper discuss HPFC as an effective FACTS device and its results are compared to UPFC and SSSC for transient stability improvement.

KEYWORDS: Power Flow Controller, FACTS Controllers, HPFC, UPFC, SSSC.

I.INTRODUCTION

Electrical energy is an essential ingredient for all-round development of any country. Electricity generated in bulk and transmitted economically over long distances. . Modern power systems are highly complex and are expected to fulfil the growing demands of power wherever required, with good quality and reduced costs. Power systems are also highly interconnected involving connections inside utilities' own territories, which extend to inter-utility interconnections and then to inter-regional and international connections. However, there is also a drawback of ac system interconnection, the security can be adversely affected as the disturbances initiated in a particular area can spread over the entire system causing cascading outages and hence resulting in major blackouts.The large interconnected transmission networks (made up of mostly overhead transmission lines) are prone to faults caused by lightning discharges and decrease in insulation clearances by undergrowth. The occurrence of a contingency such as that caused due to the tripping of a line, generator, etc., can result in a sudden increase/decrease in the power flow. This can result in overloading of some lines and consequent threat to system security.FACTS-devices can be utilized to increase the transmission capacity, improve the dynamic behaviour and stability or ensure better power quality in modern power systems. Power flow controller and a method for controlling the flow of active and reactive power on an AC transmission line is discussed in this paper. In particular, it relates to the improvement of first swing stability limit (transient stability) of a single machine infinite bus system following a fault with the help of FACTS Controller.

II.SYSTEM MODEL AND ASSUMPTIONS

This paper presents the results of the proposed technique of improving the transient stability limit by using a HPFC. The proposed control strategy is tested on the SMIB system. By keeping one of the series converter inactive, the HPFC can be operated as a UPFC and by keeping only one of the series converters active, the HPFC can be operated as a SSSC and the corresponding dynamic behaviour of the system is evaluated and compared in this paper.Consider a single machine infinite bus (SMIB) system with a HPFC as shown in Fig.1(a). The equivalent circuit of the system is shown in Fig.1(b).Where the HPFC is represented by two series voltage sources and a shunt current source. X1 represents the equivalent reactance between the machine internal bus and intermediate bus m, and X2 represents the equivalent reactance between bus n and the infinite bus in fig.1(b). Here reactance of both series transformers is neglected. The dynamics of the machine, in classical model, can be represented by the following differential equations.

$$d\delta/dt=\omega \quad (1)$$

$$d\omega/dt=1/M(P_m-P_e-D\omega) \quad (2)$$

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Here δ, ω, M, D, Pm and Pe are the angle, speed, moment of inertia, damping constant, input mechanical power and output electrical power, respectively, of the machine. The output power Pe of the machine can be expressed as

$$P_e = \mathrm{Re}(E I_1^*) \quad (3)$$

Here E is the machine internal voltage and I1 is the current through reactance X1. By using superposition theorem, I1 and I2 can be expressed as

$$I_1=\frac{E-V-V_x+V_y-jX_2 I_s}{j(X_1+X_2)} \triangleq I_1\angle\theta_1 \quad (4)$$
$$I_2=\frac{E-V-V_x+V_y+jX_1 I_s}{j(X_1+X_2)} \triangleq I_2\angle\theta_2 \quad (5)$$

Here V is the voltage at the infinite bus and is considered as reference. The voltage at bus m can be written as

$$V_m=E-V_x-jX_1 I_1 \triangleq V_m\angle\delta_m \quad (6)$$

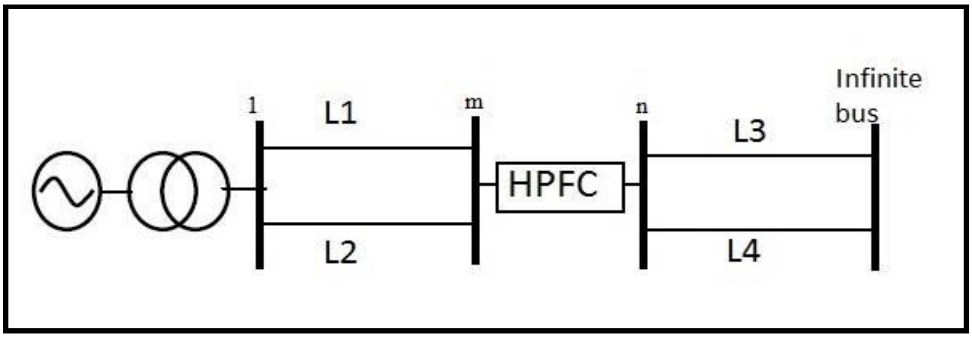

Fig.1(a) : Single line diagram of a SMIB system with HPFC

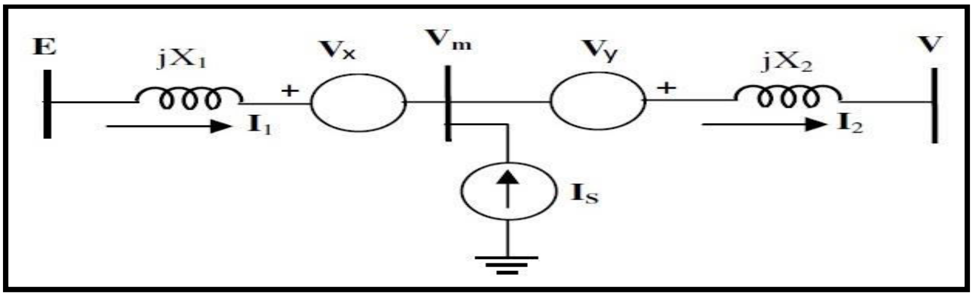

Fig.1(b) : Equivalent circuit of a SMIB system with HPFC

For given machine internal voltage E and infinite bus voltage V, currents I1 and I2 depend on the series voltage sources Vx and Vy and shunt current source Is of HPFC. When both the series converters of HPFC operates in perpendicular voltage control mode, Vx is kept in quadrature with I1 and Vy is kept in quadrature with I2 such that no real power exchange in between both the series converters. And shunt current source Is is also in quadrature with Vm. When all converters are in capacitance mode, Vx ,Vy and Is can be expressed as

$$V_x=V_x\angle(\theta_1-\pi/2) \triangleq V_x\angle\alpha \quad (7)$$
$$V_y=V_y\angle(\theta_2+\pi/2) \triangleq V_y\angle\beta \quad (8)$$
$$I_s=I_s\angle(\delta_m-\pi/2) \triangleq I_s\angle\gamma \quad (9)$$

Here θ1, θ2 and δm are the angles of I1, I2 and Vm respectively. When all converters are in inductive mode, the values are simply shifted by π with respect to capacitive mode of operation. In this work, Vx, Vy and Is are calculated by appropriate control law and angles of these quantities are obtained from the equations

$$\alpha = \theta_1 - \pi/2 \quad (10)$$
$$\beta = \theta_2 + \pi/2 \quad (11)$$

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$$\gamma = \delta m - \pi/2 \quad (12)$$

Note that there are no closed form solutions for θ1, θ2 and δm. However, for given values of Vx ,Vy and Is, values of θ1, θ2 and δm can be obtained from (4)-(6) by using the following simple iterative scheme. Assume initial values of θ1, θ2 and δm and calculate α, β and γ. using (10)-(12), respectively. Obtain I1, I2 and Vm from (4) - (6), respectively. Determine values of θ1, θ2 and δm. Update α, β and γ. using (10) - (12), respectively.Simulation block diagram of the system with a HPFC as shown in fig.1(c), by setting the parameter Vx to zero, the same block diagram can also be used to evaluate the system response with UPFC. Similarly by setting the parameters Vx and Is to zero the same block diagram can be used to evaluate the system response with SSSC. The results for all the three cases (i.e. with HPFC, UPFC and SSSC) are evaluated and compared in following sections.For a SMIB system, the stability limit can be determined through equal-area-criterion. Maximizing the first swing stability limit involves enlarging the decelerating area as much as possible and fully utilizing it in counterbalancing the accelerating area. This can be carried out by operating both the series and shunt converters of the HPFC in capacitive mode in early part of the post fault period until the machine speed reaches a reasonable negative value during the first return journey. Afterwards, a simple linear continuous control can be applied to improve damping in subsequent swings. Keeping this in mind, the same strategy is considered here for controlling HPFC parameters and it is as follows.

During fault condition (when t <tc)

Vx = 0;
Vy = 0; (13)
Is = 0;
Post fault condition (when t <tc)
If ω > -ξωm (first swing)
Vx = Vxmax;
Vy = Vymax; (14)
Is = Ismax;
Otherwise:
Vx = k1 ω ;V_x^min⩽V_x⩽V_x^max
Vy = k2 ω ; V_y^min⩽V_y⩽V_y^max (15)
Is = k3 ω ; I_s^min⩽I_s⩽I_s^max
Where k1, k2 and k3 are the positive gains and their values depend on the ratings of converters. ωm is the maximum machine speed and it usually occurs at fault clearing time tc, and ξ is a small positive constant. Vxmax and Vymax and Ismax are the maximum voltage and current ratings series and shunt converters, respectively of HPFC. Here the values of Vx ,Vy and Is are calculated by using the above control strategy.

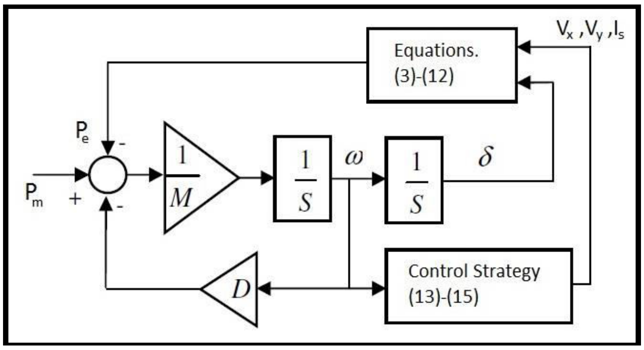

Fig.1(c): Simulation block diagram of the SMIB system with HPFC

The MatlabSimulink model of the SMIB system with HPFC as shown below. The values of the series voltage magnitude Vx and Vy and the shunt current magnitude Is of the HPFC are controlled dynamically using the proposed control strategy and thus the output power is controlled accordingly.

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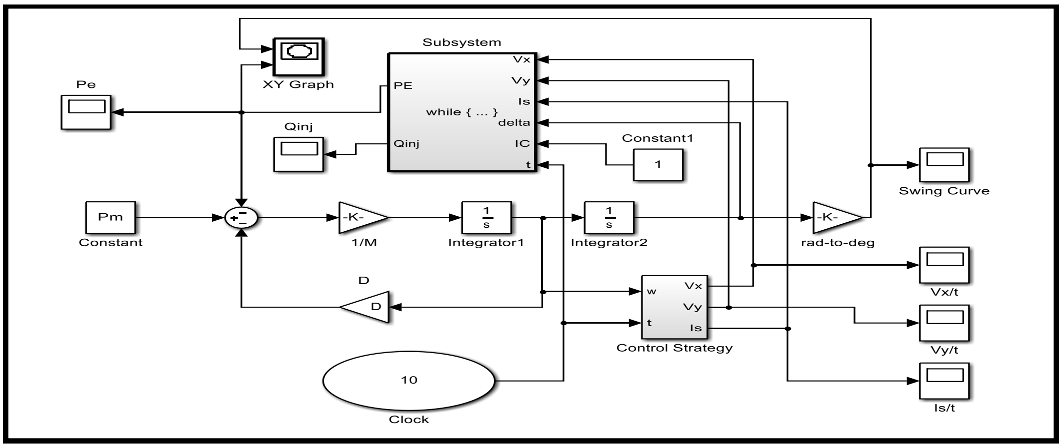

Fig.2 (a)

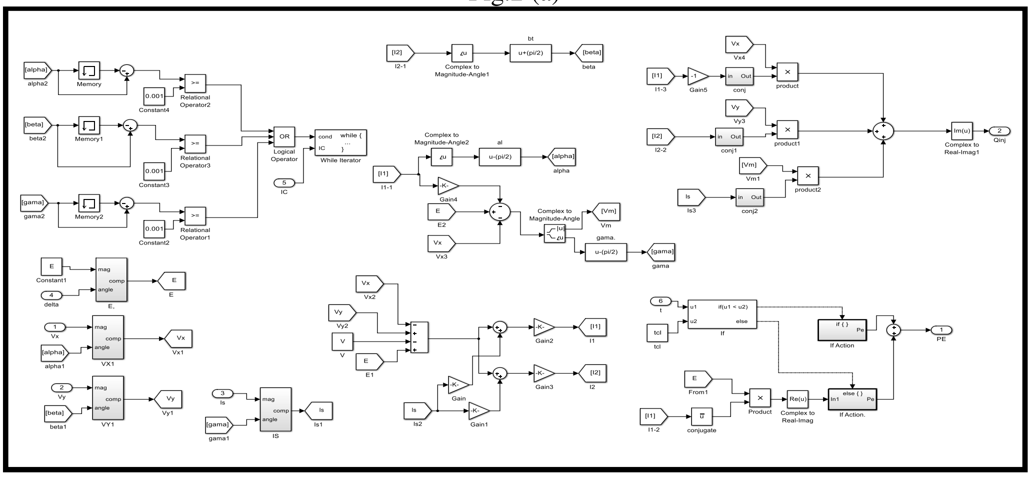

Fig.2(b)

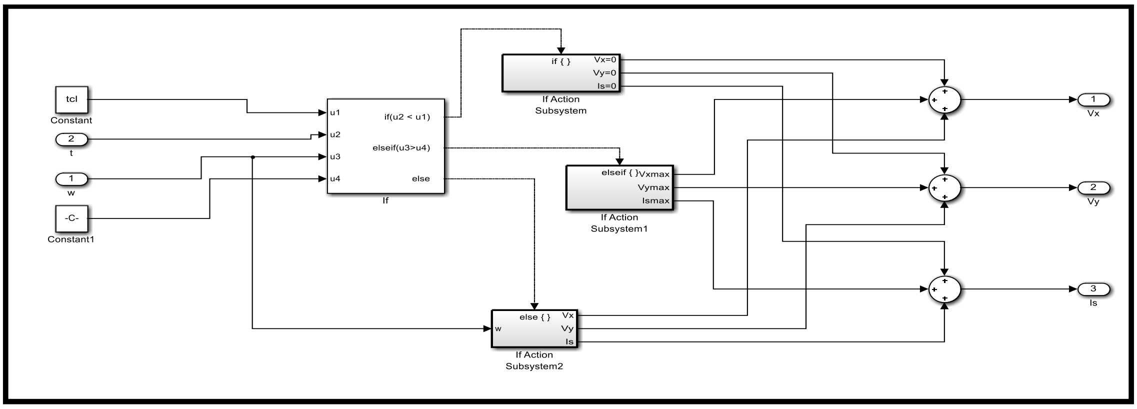

Fig.2(c)

Fig.2: Matlab Simulink model of (a) the SMIB system with HPFC (b) the subsystem for carrying out calculations of various equations involved to determine output power (c) the control strategy to dynamically control magnitude of parameters of HPFC i.e. Vx, Vy and Is.The subsystem in Fig.2 (b) calculates all the equations required to compute the output power according to the dynamic values of Vx,Vy and Is

III.SIMULATION RESULTS WITH SSSC

The Simulink block diagram shown in Fig.2 with HPFC can be used to obtain the system's dynamics response for SSSC operation by setting values of Vx and Is to zero and Vy as 0.2 pu.

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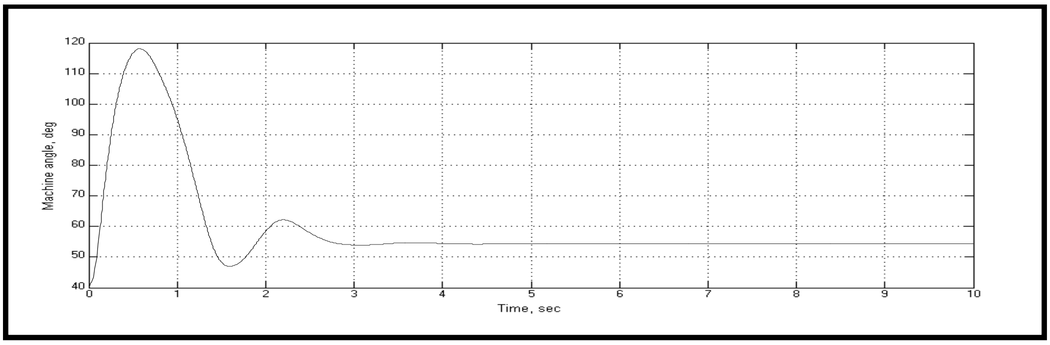

Fig.3: Swing Curve for SSSC operation with fault clearing time 135 ms

The swing curve of the machine obtained by operating the HPFC as a SSSC for a fault clearing time of 135 ms as shown in Fig.3. It is observed that when the HPFC operates as a SSSC, the machine has the highest peak angle of 118° during the first swing. The stable angle is found to 54.14°.Stable angles peak angles and settling times for different fault clearing times are calculated.

We observe that as the fault clearing time is increased it decreases the transient stability margin by increasing the maximum peak angle of first swing, stable rotor angle and settling time of the rotor angle. Results indicate that, with the SSSC (when Vx =0, Vy = 0.2 and Is = 0), the Critical Clearing Time (CCT) of the fault is 140 ms.

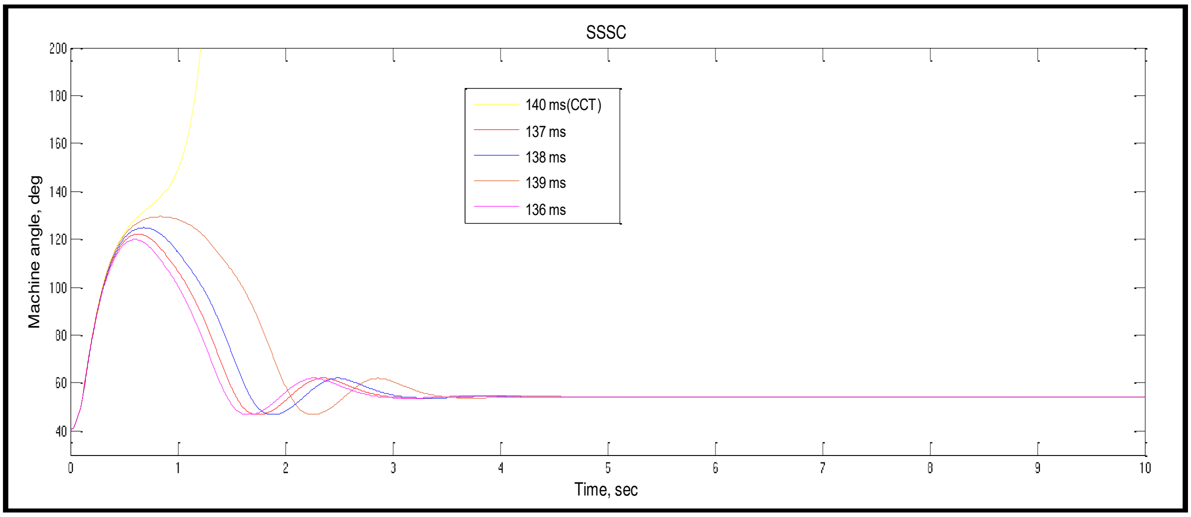

Fig.4 : Swing curves for SSSC operation for different fault clearing times.

IV.SIMULATION RESULTS WITH UPFC

By setting one of the series converters of HPFC (Vx) to zero keeping Vy and Is active with their ratings 0.2 pu and 0.5 pu respectively, the same Simulink block diagram shown in Fig.2 with HPFC can be used to obtain the system's dynamics response for UPFC operation.

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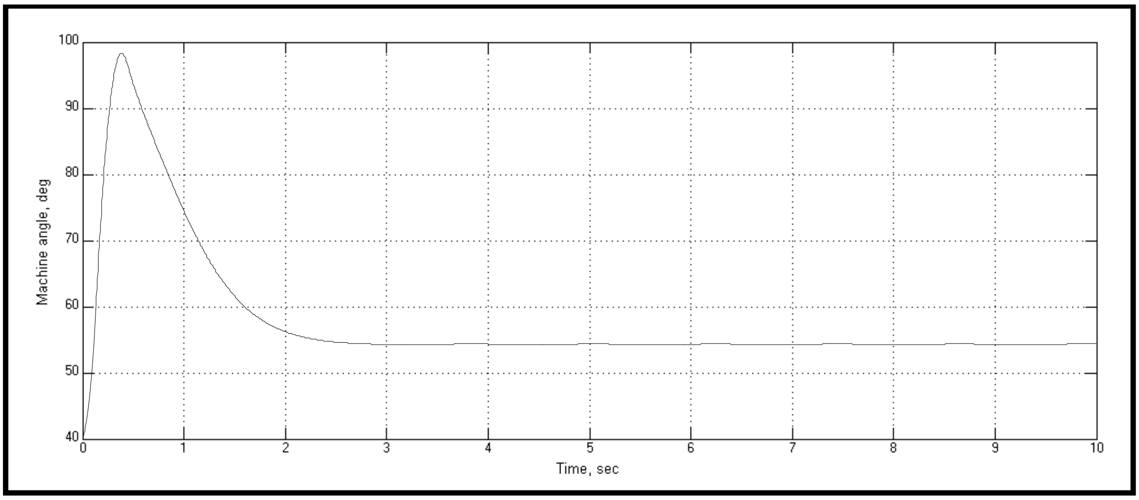

Fig.5: Swing Curve for UPFC operation with fault clearing time 135 ms

The swing curve of the machine obtained by operating the HPFC as a UPFC for a fault clearing time of 135 msis shown in Fig.5. It can be observed that when the HPFC operates as a UPFC, the machine has the highest peak angle of 98.27° during the first swing. The stable angle is found to 54.20°.Stable and peak angles and settling time for different fault clearing times are calculated.

We observe that as the fault clearing time is increased it decreases the transient stability margin by increasing the maximum peak angle of first swing, stable rotor angle and settling time of the rotor angle. Results indicate that, with the UPFC (when Vx =0, Vy = 0.2 and Is = 0.5), the Critical Clearing Time (CCT) of the fault is 169 ms.

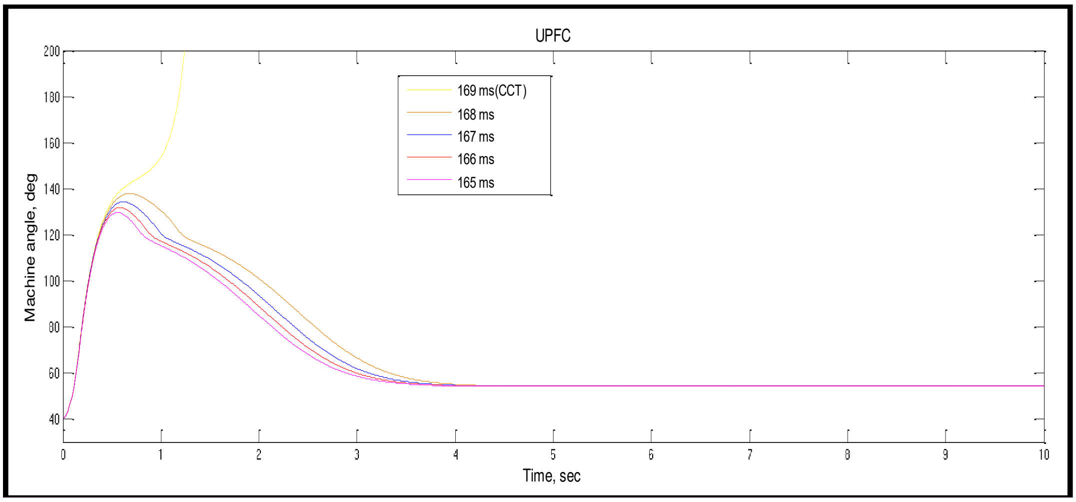

Fig.6 : Swing curves for UPFC operation for different fault clearing times.

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V.SIMULATION RESULTS WITH HPFC

In the case of HPFC operation, all the converters Vx, Vy and Is are kept active with their ratings considered as 0.2 pu, 0.2 pu and 0.5 pu, respectively.

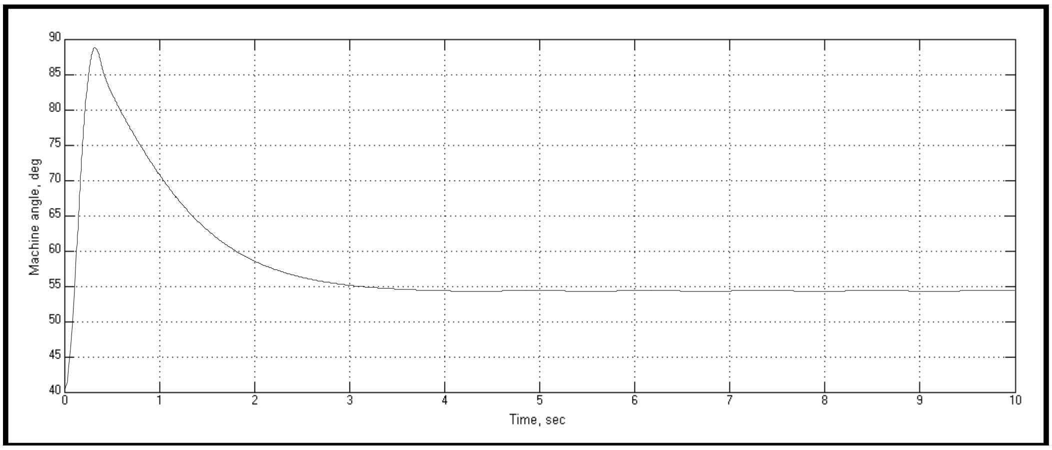

Fig.7 : Swing Curve for HPFC operation with fault clearing time 135 ms

The swing curve of the machine, with the HPFC, for a fault clearing time of 135 msis shown in Fig.7. It can be observed that with the HPFC operation the machine has the highest peak angle of 88.73o during the first swing. The stable angle is found to 54.27°.Stable and peak angles and settling time for different fault clearing times are tabulated here. Table 1 gives the results when the device operated as HPFC.

TABLE1: Stable and peak angles and settling time for different fault clearing times with HPFC

Fault clearing time (ms)	Peak of 1st swing (deg)	Stable rotor angle (deg)	Settling time (sec)
140	92	54..28	3.13
141	92.6	54.28	3.14
142	93.26	54.281	3.16
143	94	54.281	3.17
144	94.62	54.282	3.196
145	95.31	54.282	3.21
146	96	54.283	3.23
147	96.7	54.286	3.25
152	100.39	54.3	3.37
153	101.16	54.3	3.4
154	101.94	54.312	3.42
155	102.73	54.312	3.45
156	103.53	54.313	3.48
157	104.35	54.314	3.51
158	105	54.314	3.54
159	106	54.315	3.57
160	106.88	54.316	3.6
165	111.43	54.32	3.78
166	112.4	54.321	3.82
167	113.4	54.322	3.86

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168	114.42	54.323	3.9
169	115.47	54.323	3.93
170	116.55	54.326	3.98
171	117.67	54.328	4.02
184	139.8	54.35	5.07
185	145	54.35	5.47
186	Unstable	---	---

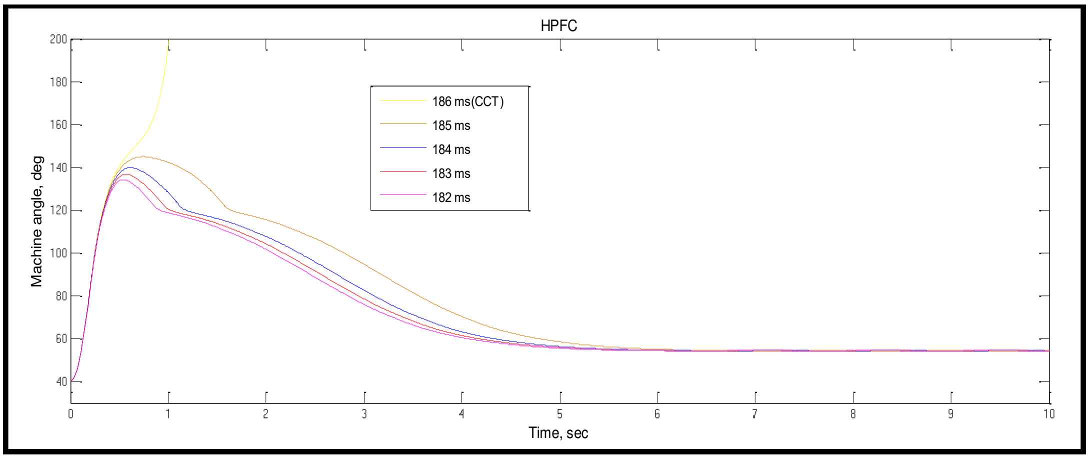

Fig.8: Swing curves for HPFC operation for different fault clearing times.

We observe that as the fault clearing time is increased it decreases the transient stability margin by increasing the maximum peak angle of first swing, stable rotor angle and settling time of the rotor angle. Results of Table-1 indicate that, with the HPFC (when Vx =0.2, Vy = 0.2 and Is = 0.5), the Critical Clearing Time (CCT) of the fault is 186 ms.
The variation of Vx , Vy and Is for the above fault case is shown in Fig.9 and it also indicates that all the series and shunt converters of the HPFC operate at full capacitive ratings in early part of the post fault period to maximize the first swing stability limit.

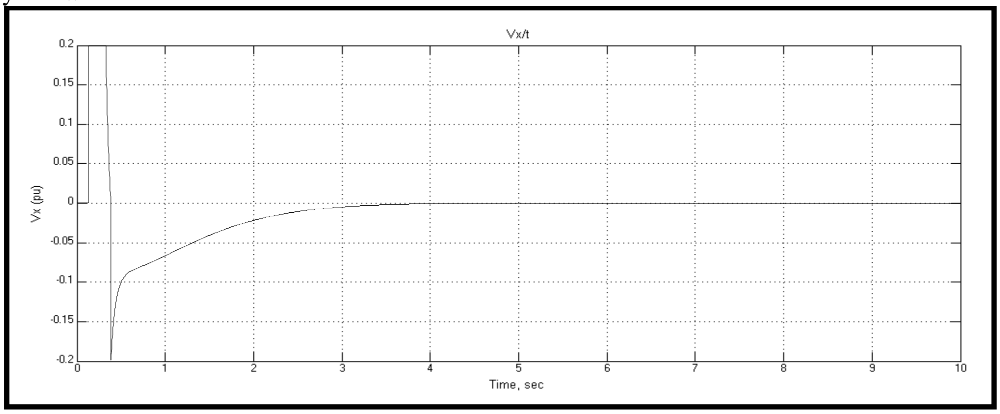

Fig.9: Variation of (a) Vx

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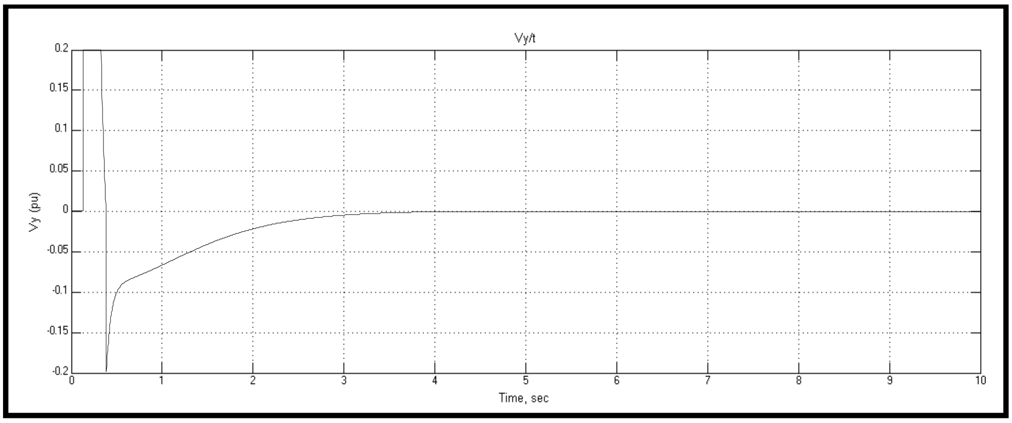

Fig.9: Variation of (b) Vy

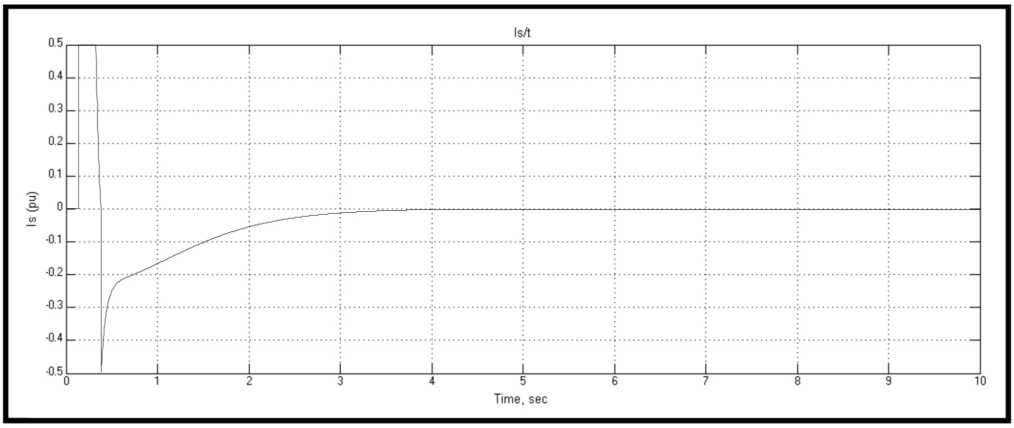

Fig.9: Variation of (c) Is

V. RESULT AND DISCUSSION

a) Swing Curves:By observing waveforms of SMIB system for machine rotor angle v/s time for the three cases HPFC, UPFC and SSSC, it can be seen that HPFC has the highest stability margin as the system has the lowest value of peak angle of 88.73° during the first swing in the case of HPFC operation and also it provides maximum damping in subsequent swings.

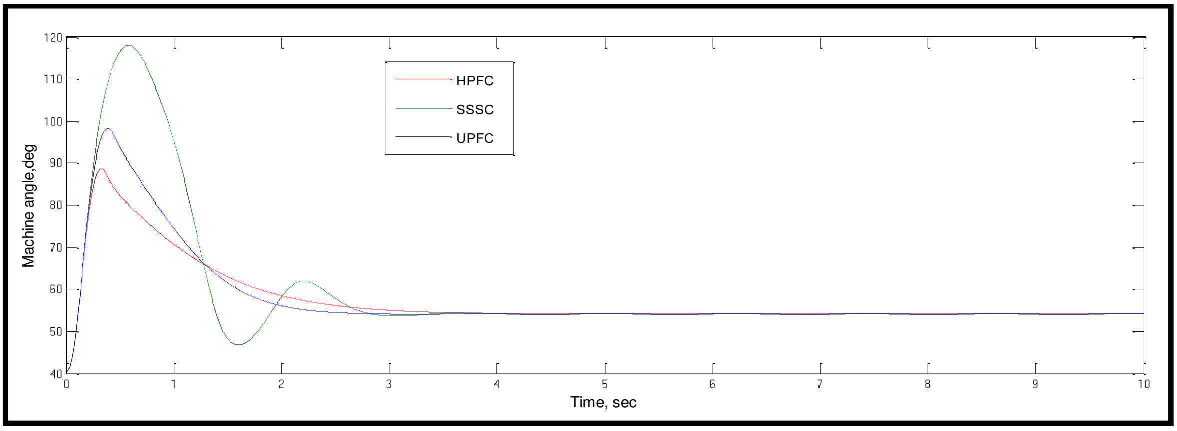

Fig. 10: Swing curves of the machine with HPFC, UPFC and SSSC

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Thus from the simulation results, it is inferred that HPFC is an effective FACTS device for transient stability improvement compared to SSSC and UPFC. The above results are tabulated below:

TABLE-2: Stable and peak angles and settling time for fault clearing time 135 ms with HPFC, UPFC and SSSC

FACTS Controller	Stable rotor angle (deg)	Peak of 1st swing (deg)	Settling time (sec)
SSSC	54.22	69.90	2.66
UPFC	54.27	85.69	2.37
HPFC	54.28	92	3.07

b) Critical Clearing Time (CCT) with SSSC, UPFC and HPFC:The maximum allowable value of the fault clearing time for the system to remain stable is known as the critical clearing time. The values of CCTs with device operated as SSSC, UPFC and HPFC is shown in the Table 3 below. We can observe that the value of CCT ismaximum for HPFC operation and hence the maximum improvement in transient stability of the power system under fault condition is observed in this case.

TABLE-3: CCT , peak angle, stable rotor angle and settling time with HPFC, UPFC and SSSC

Fault clearing time (ms)	**Peak of 1st swing (deg)**			**Stable rotor angle (deg)**			**Settling time (sec)**		
	SSSC	**UPFC**	**HPFC**	**SSSC**	**UPFC**	**HPFC**	**SSSC**	**UPFC**	**HPFC**
100	85.82	77.48	69.90	54.12	54.16	54.22	2.162	1.82	2.45
130	110.75	94.80	85.69	54.14	54.19	54.27	2.49	2.166	3.01
140(CCT-SSSC)	---	102	92	---	54.20	54.28	---	2.32	3.13
160	---	121.57	106.88	---	54.22	54.32	---	3	3.6
169(CCT-UPFC)	**---**	---	115.47	---	---	54.33	---	---	3.93
180	**---**	---	130.15	---	---	54.35	---	---	4.7
186(CCT-HPFC)	**---**	---	---	---	---	---	---	---	---

c) Variation of real power output: The variation of real power output of SMIB system with device operated as HPFC is shown in fig.11. And with HPFC operated as UPFC and SSSC is also shown for comparison purpose. It indicates that system with HPFC transfers max power when compared with UPFC and SSSC and settling time is also less comparatively.

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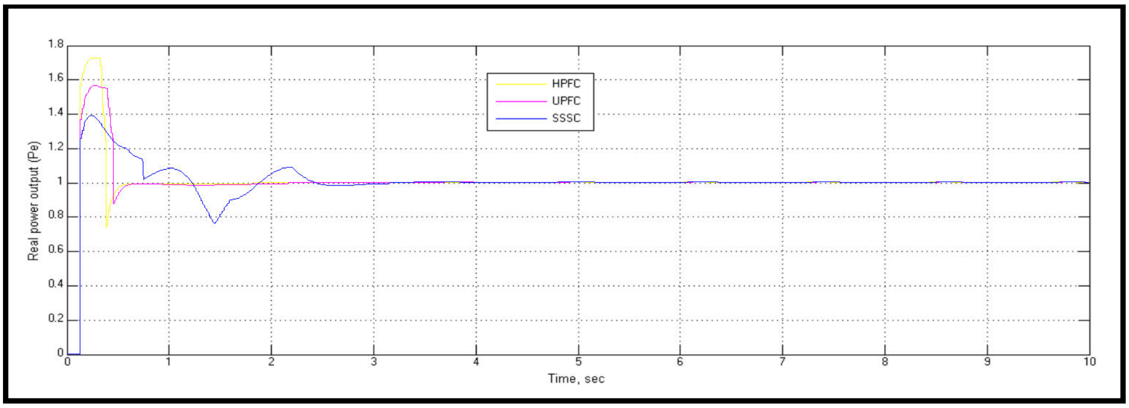

Fig.11 : Variation of real output power (Pe) with HPFC, UPFC and SSSC

d) Variation of total reactive power injected: The variation of total reactive power injected by the FACTS device (for HPFC, UPFC and SSSC operations) is shown in Fig.12 and it indicates that the HPFC injects the highest value of reactive power in early part of the post fault period but its duration is shorter compared to that for the UPFC and SSSC operation.

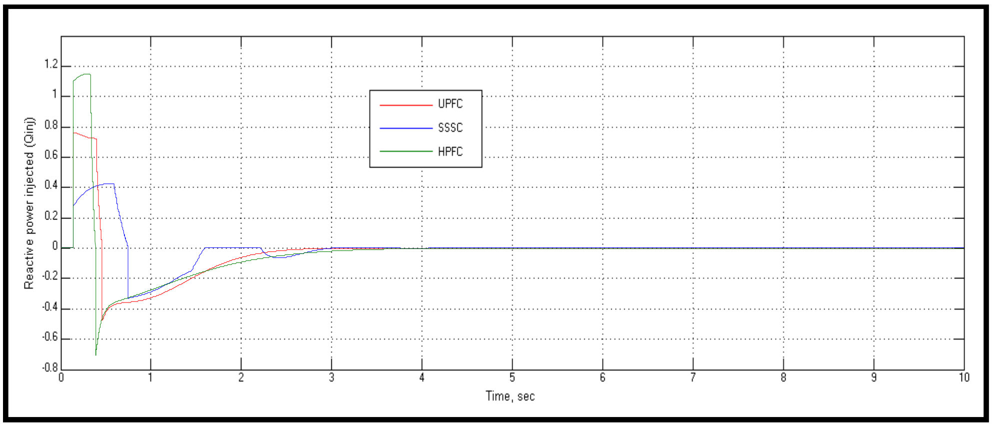

Fig.12 : Reactive power injected by HPFC, UPFC and SSSC

VI.CONCLUSION

All the equations used in improving the stability limit by using HPFC are systematically derived. The same equations can also be used to represent a SSSC or a UPFC by setting some of the control parameters of the HPFC to zero and the results found for various operations of the HPFC are also compared with SSSC and UPFC. The superiority of a HPFC over a SSSC or a UPFC in improving the dynamic performance of a power system is also demonstrated. From the simulation results, it is inferred that HPFC is an effective FACTS device for transient stability improvement.

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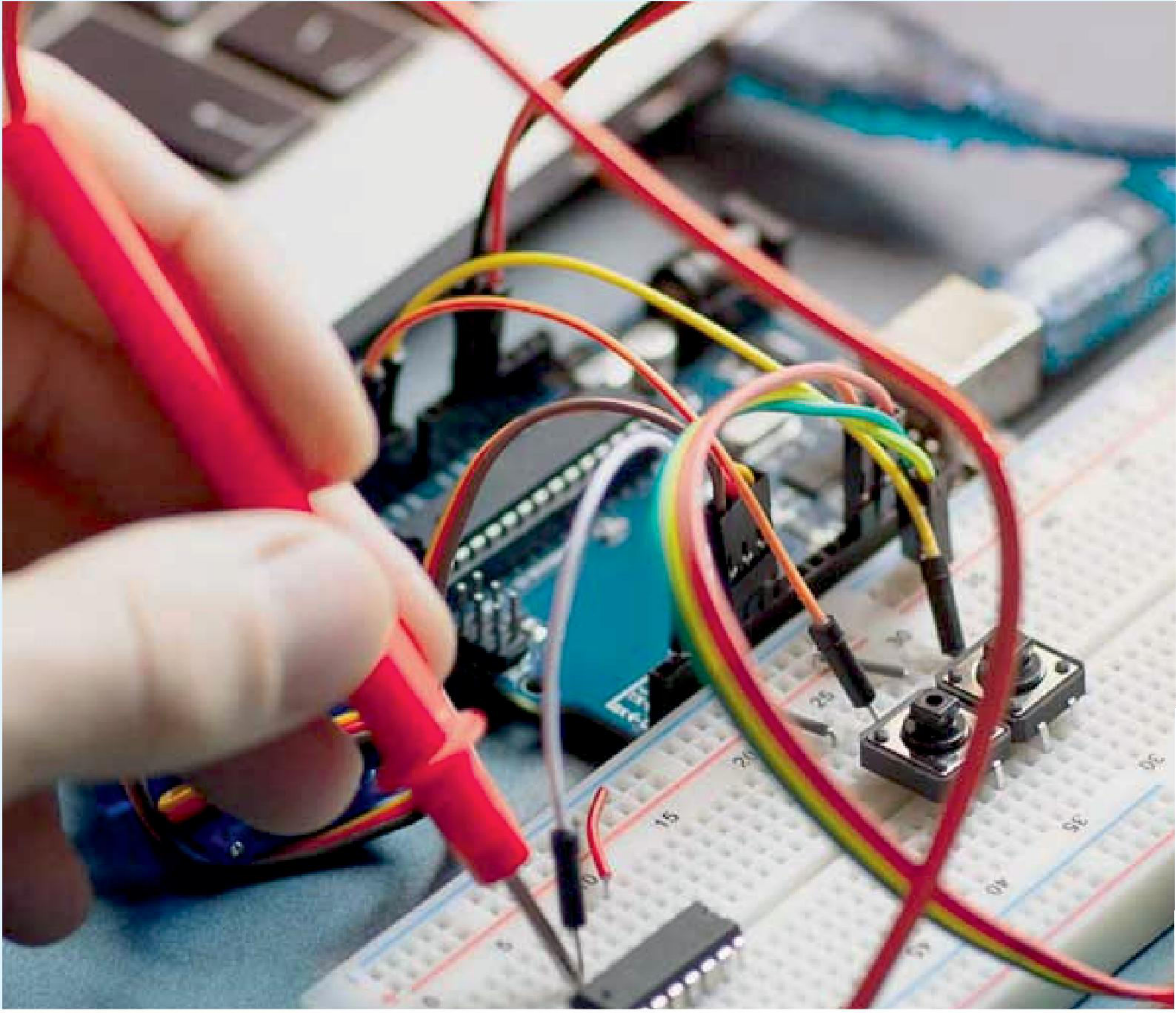

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