ANN BASED STATCOM ALONG LARGE COMPENSATION RANGE AND LESS DC-LINK VOLTAGE FORLOADS

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Abstract-A TCLC-STATCOM in three-phase power system is proposed and discussed as a cost-effective reactive power compensator for low voltage level application in this paper using ANN. Because of these prominent characteristics, the system costs can be greatly reduced. Its V-I characteristic is then analyzed, discussed, and compared with traditional STATCOM and capacitive-coupled STATCOM (C-STATCOM). The system parameter design is then proposed on the basis of consideration of the reactive power compensation range and avoidance of the potential resonance problem. After that, a control strategy for TCLC-STATCOM is proposed to allow operation under different voltage and current conditions, such as unbalanced current, voltage dip, and voltage fault. By using the simulation results we can verify the wide compensation range and low DC-link voltage characteristics and the good dynamic performance of the proposed TCLC-STATCOM.

Index Terms—Capacitive-coupled static synchronous compensator (C-STATCOM), TCLC-STATCOM, low dc-link voltage, STATCOM, wide compensation range, ANN.

INTRODUCTION

A TCLC-STATCOM is proposed,with the distinctive characteristics of a much wider compensation range than C-STATCOM [10] and other series-type PPF-STATCOMs and a much lower DC-link voltage than traditional STATCOM [4]-[9] and other parallel-connected TCLC STATCOMs. To improve the operating performances of the traditional STATCOMs, C-STATCOMs, and other PPF- STATCOMs, many different control techniques have been proposed. The large reactive current in transmission systems is one of the most common power problems that increases transmission losses and lowers the stability of a power system [1]. Application of reactive power compensators is one of the solutions for this issue.

StaticVAR compensators (SVCs) are traditionally used to dynamically compensate reactive currents as the loads vary from time to time However, SVCs suffer from many problems, such as resonance problems, harmonic current injection, and slow response [2]-[3]. To overcome these disadvantages, static synchronous compensators (STATCOMs) and active power filters (APFs) were developed for reactive current compensation with faster response, less harmonic current injection, and better performance [4]-[9]. However, the STATCOMs or APFs usually require multilevel structures in a medium- or high-voltage level transmission system to reduce the high-voltage stress across each power switch and DC-link capacitor, which drives up the initial and operational costs of the system and also increases the control complexity. A new control strategy for TCLC-STATCOM is proposed to coordinate the TCLC part and the active inverter part for reactive power compensation under different voltage and current conditions, such as unbalanced current, voltage fault, and voltage dip.

To reduce the current rating of the STATCOMs or APFs, a TCLC combination structure of PPF in parallel with STATCOM was proposed. However, this TCLC compensator is dedicated for inductive loading operation. When it is applied for capacitive loading compensation, it easily loses its small active inverter rating characteristics..

To overcome the shortcomings of different reactive power compensators [1]-[22] for transmission systems, this paper proposes a TCLC- STATCOM that consists of a thyristor-controlled LC part (TCLC) and an active inverter part, as shown in Fig. 1. The TCLC part provides a wide reactive power compensation range and a large voltage drop between the system voltage and the inverter voltage so that the active inverter part can continue to operate at a low DC-link voltage level.The small rating of the active inverter part is used to improve the performances of the TCLC part by absorbing the harmonic currents generated by the TCLC part, avoiding mistuning of the firing angles, and preventing the resonance problem

CIRCUIT CONFIGURATION OF THE TCLC- STATCOM

Fig. 1 shows the circuit configuration of TCLC-STATCOM,in which the subscript"x"stands for phase a,b,and c in the following analysis.vsx and vx are the source and load voltages; isx, iLx,and icx are the source,load,and compensating currents, respectively.Ls is the transmission line impedance. The TCLC-STATCOM consists of a TCLC and an active inverter part. The TCLC part is composed of a coupling inductor Lc, a parallel capacitor CPF, and a thyristor-controlled reactor with LPF. The TCLC part provides a wide and continuous inductive and capacitive reactive power compensation range that is controlled by controlling the firing angles αx of the thyristors.

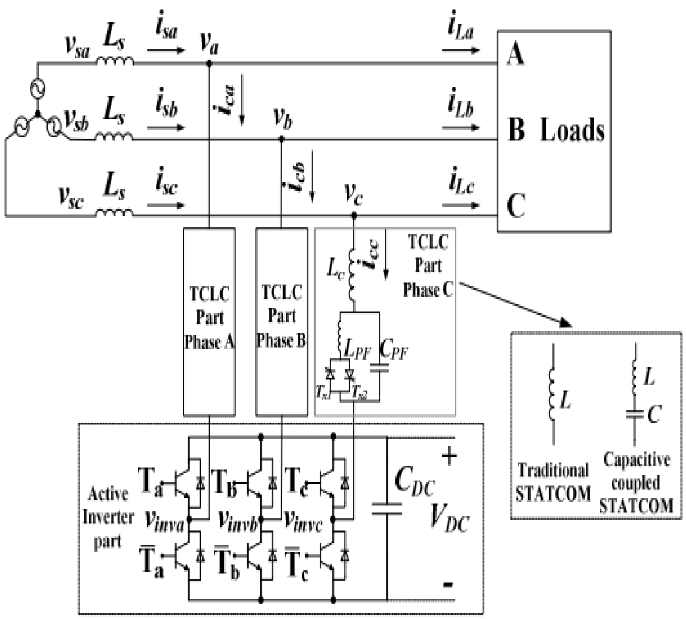


Fig. 1. Circuit configuration of the TCLC- STATCOM.

The active inverter part is composed of a voltage source inverter with a DC-link capacitor Cdc, and the small rating active inverter part is used to improve the performance of the TCLC part. In addition, the coupling components of the traditional STATCOM and C-STATCOM are also presented in Fig. 1.The characteristics of different reactive power compensators and the proposed TCLC STATCOM for the transmission system are compared and summarized in Table I.

TABLE I

CHARACTERISTICS OF DIFFERENT COMPENSATORS FOR TRANSMISSION SYSTEM

	Response time	Resonance problem	DC-link voltage	Compensation range	Cost
SVCs [2]-[3]	Slow	Yes	--	Wide	Low
STATCOMs [4]-[9]	Very Fast	No	High	Wide	High
C-STATCOMs [10]	Fast	No	Low	Narrow	Low
Series-type PPF-STATCOMs [11]-[19]	Fast	No	Low	Narrow	Low
PPF//STATCOM [20], [21]	Fast	Yes	High	Narrow	Medium
SVC//APF [22]	Fast	Yes	High	Wide	High
Hybrid-STATCOM	Fast	No	Low	Wide	Medium

The purpose of the TCLC-STATCOM is to provide the same amount of reactive power as the loadings (QLx) consumed, but with the opposite polarity (Qcx=-QLx). The TCLC-STATCOM compensating reactive power Qcx is the sum of the reactive power QTCLC that is provided by the TCLC part and the reactive power Qinvx that is provided by the active inverter part. Therefore, the relationship among QLx, QTCLC, and Qinvx can be expressed as

$$Q_{Lx}=-Q_{cx}=-(Q_{TCLC}+Q_{invx}) \qquad (1)$$

The reactive powers can also be expressed iterms of voltages and currents as

$$Q_{Lx}=V_xI_{Lqx}=-(X_{TCLC}(\alpha_x)I2_{cqx}+V_{invx}I_{cqx}) \qquad (2)$$

where XTCLC(αx) is the coupling impedance of the TCLC part; αx is the corresponding firing angle; Vx and Vinvx are the root mean square (RMS) values of the coupling point and the inverter voltages; and ILqx and Icqx are the RMS value of the load and compensating reactive currents, where ILqx=-Icqx. Therefore, (2) can be further simplified as

$$V_{invx}=V_x+X_{TCLC}(\alpha_x)I_{Lqx} \qquad (3)$$

$$X_{TCLC}(\alpha_x)=\frac{X_{TCR}(\alpha_x)X_{C_{pf}}}{X_{C_{pf}}-X_{TCR}(\alpha_x)}+X_{Lc}=\frac{\pi X_{L_{pf}}X_{C_{pf}}}{X_{C_{pf}}(2\pi-2\alpha_x+\sin 2\alpha_x)-\pi X_{L_{pf}}}+X_{Lc} \qquad (4)$$

where the TCLC part impedance XTCLC(αx) can be expressed as where X Lc , XLPF , and XCPF are the fundamental impedances of Lc, LPF, and CPF respectively. In (4), it is shown that the TCLC part impedance is controlled by firing angle αx. And the minimum inductive and capacitive impedances (absolute value) of the TCLC part can be obtained by substituting the firing angles αx=90o and αx=180o, respectively. In the following discussion, the minimum value for impedances stands for its absolute value. The minimum inductive (Xind(min)>0) and capacitive (XCap(min)<0) TCLC part impedances can be expressed as

$$X_{Ind(min)}(\alpha_x = 90^0) = \frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_c} \qquad (5)$$

$$X_{Cap(min)}(\alpha_x = 180^0) = -X_{C_{PF}} + X_{L_c} \qquad (6)$$

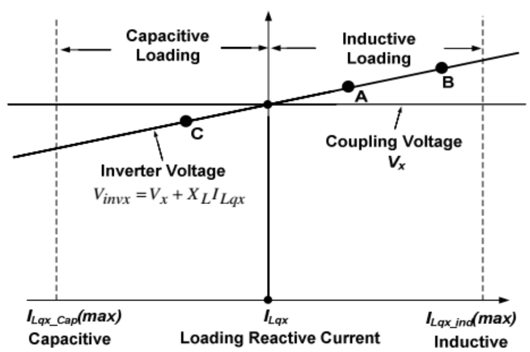
Ideally, XTCLC(αx) is controlled to be x ≈α I)(XV LqxxTCLC , so that the minimum inverter voltage (invx ≈ 0V) can be obtained as shown in (3). In this case, the switching loss and switching noise can be significantly reduced. A small inverter voltage Vinvx(min) is necessary to absorb the harmonic current generated by the TCLC part, to prevent a resonance problem, and to avoid mistuning the firing angles. If the loading capacitive current or inductive current is outside the TCLC part compensating range, the inverter voltage Vinvx will be slightly increased to further enlarge the compensation range.

The coupling impedances for traditional STATCOM and C-STATCOM, as shown in Fig. 1, are fixed as XL and XC-1/XL. The relationships among the load voltage Vx, the inverter voltage Vinvx, the load reactive current ILqx, and the coupling impedance of traditional STATCOM and C- STATCOM can be expressed as

$$V_{invx} = V_x + X_L I_{Lqx} \qquad (7)$$

$$V_{invx} = V_x - \left(X_C - \frac{1}{X_L}\right) I_{Lqx} \qquad (8)$$

where XL >> XC.



(a)

Fig. 2. V-I characteristic of (a) traditional STATCOM,

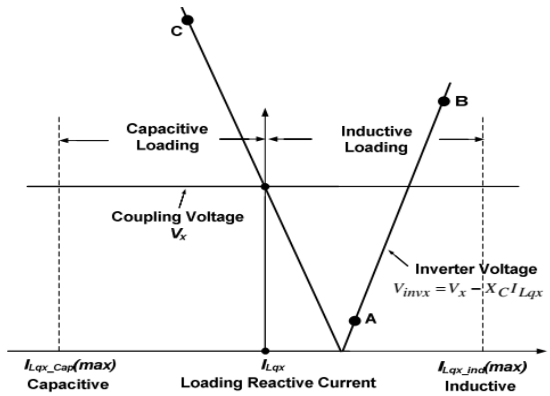
Based on (3)-(8), the V-I characteristics of the traditional STATCOM, C- STATCOM, and TCLC-STATCOM can be plotted as shown in Fig. 2.

For traditional STATCOM as shown in Fig.2(a), the required Vinvx is larger than Vx when the loading is inductive. In contrast, the required Vinvx is smaller than Vx when the loading is capacitive. Actually, the required inverter voltage Vinvx is close to the coupling voltage Vx, due to the small value of coupling inductor L [5]-[8].

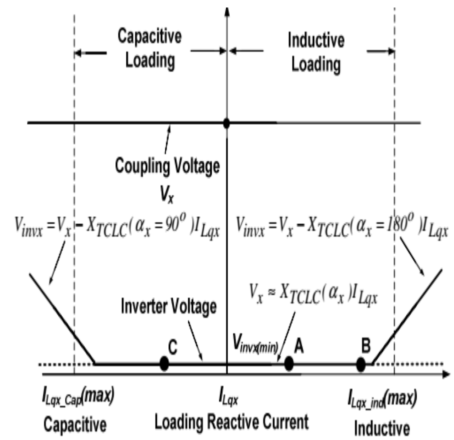
For C-STATCOM as shown in Fig. 2(b), it is shown that the required Vinvx is lower than Vx under a small inductive loading range.

The required Vinvx can be as low as zero when the coupling capacitor can fully compensate for the loading reactive current. In contrast, Vinvx is larger than Vx when the loading is capacitive or outside its small inductive loading range. Therefore, when the loading reactive current is outside its designed inductive range, the required Vinvx can be very large.

For the proposed TCLC-STATCOM as shown in Fig. 2(c), the required Vinvx can be maintained at a low (minimum) level (Vinvx(min)) for a large inductive and capacitive reactive current range.



(b)



(c)

IV. PARAMETER DESIGN OF TCLC- STATCOM

The proposed TCLC part is a newly proposed SVC structure which designed based on the basis of the consideration of the reactive power compensation range (for LPF and CPF) and the prevention of the potential resonance problem (for Lc). The active inverter part (DC-link voltage VDC) is designed to avoid mistuning of the firing angle of TCLC part.

A.Design of CPF and LPF

The purpose of the TCLC part is to provide the same amount of compensating reactive power Qcx,TCLC(αx) as the reactive power required by the loads QLx but with the opposite direction. Therefore, CPF and LPF are designed on the basis of the maximum capacitive and inductive reactive power. The compensating reactive power Qcx range in term of TCLC impedance XTCLC(αx) can be expressed as TCLC part, which can be obtained from (4). In (9), when the XTCLC(αx)=XCap(min)(αx =180o) and XTCLC(αx)=XInd(min)(αx =90o), the TCLC part provides the maximum capacitive and inductive compensating reactive power Qcx(MaxCap) and Qcx(MaxInd), respectively

$$Q_{cx(MaxCap)} = \frac{V_x^2}{X_{Cap(min)}(\alpha_x=180^0)} = -\frac{V_x^2}{X_{C_{PF}}-X_{L_C}} \quad (10)$$

$$Q_{cx(MaxInd)} = \frac{V_x^2}{X_{Ind(min)}(\alpha_x=90^0)} = -\frac{V_x^2}{\frac{X_{C_{PF}}X_{L_{PF}}}{X_{C_{PF}}-X_{L_{PF}}}+X_{L_C}} \quad (11)$$

where the minimum inductive impendence XInd(min) and the capacitive impendenceXCap(min) are obtained from (5) and (6), respectively

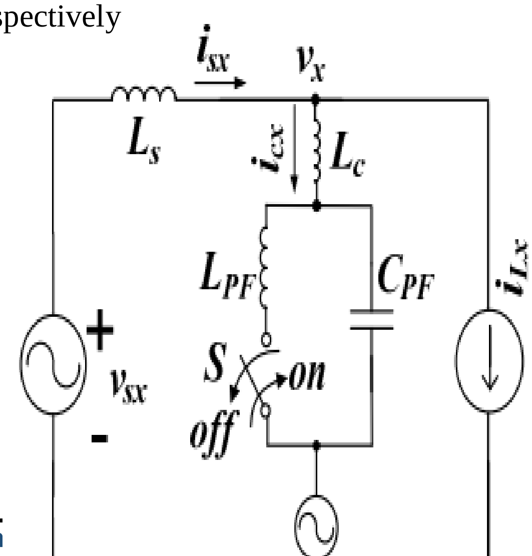


Fig. 3. Simplified single-phase equivalent circuit model of TCLC-STATCOM.

Referring to Fig. 3, when switch S is turned off, the TCLC part can be considered as the Lc in series with CPF, which is called LC-mode. The TCLC part harmonic impedances under LC-mode and LCL- mode at different harmonic order n can be plotted in fig 4 and expressed as

$$X_{LC,n}(n) = \left|\frac{1-(n\omega)^2 L_C C_{PF}}{n\omega C_{PF}}\right| \qquad (12)$$

$$X_{LC,n}(n) = \left|\frac{n\omega(L_c+L_{PF})-(n\omega)^3 L_{PF} L_c C_{PF}}{1-(n\omega)^2 L_{PF} C_{PF}}\right| \qquad (13)$$

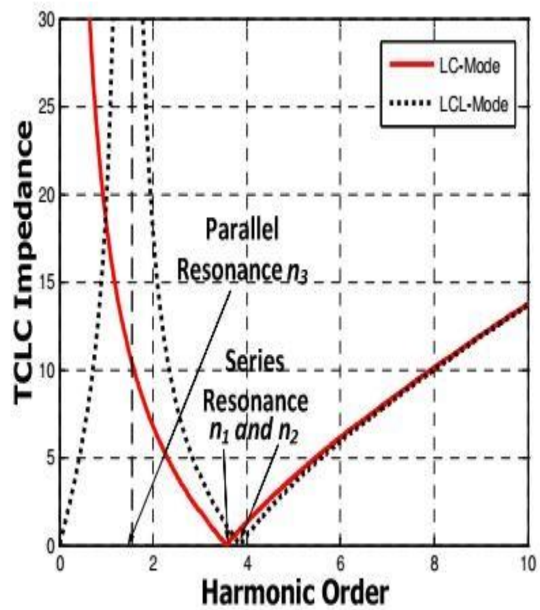


Fig. 4. TCLC impedance under different harmonic order.

B.Design of VDC

Different with the traditional VDC design method of the STATCOM to compensate maximum load reactive power, the VDC of TCLC-STATCOM is design to solve the firing angle mistuning problem of TCLC (i.e., affect the reactive power compensation) so that the source reactive power can be fully compensated. Reforming (3), the inverter voltage Vinvx can also be expressed as

$$V_{incx} = V_x\left[1+\frac{V_x I_{Lqx}}{V_x^2/X_{TCLC}(\alpha_x)}\right] = V_x\left[1+\frac{Q_{Lx}}{Q_{cx,TCLC}(\alpha_x)}\right] \qquad (14)$$

Where QLx is the load reactive power, Qcx,TCLC(αx) is the TCLC part compensating reactive power, and Vx is the RMS value of the load voltage

V. CONTROL STRATEGY OF TCLC- STATCOM

A control strategy for TCLC-STATCOM is proposed by coordinating the control of the TCLC part and the active inverter part so that the two parts can complement each other's disadvantages and the overall performance of TCLC-STATCOM can be improved. The control strategy of TCLC-STATCOM is separated into two parts for discussion: A. TCLC part control and B. Active inverter part control. The response time of TCLC-STATCOM is discussed in part C. The control block diagram of TCLC- STATCOM is shown in Fig. 5.

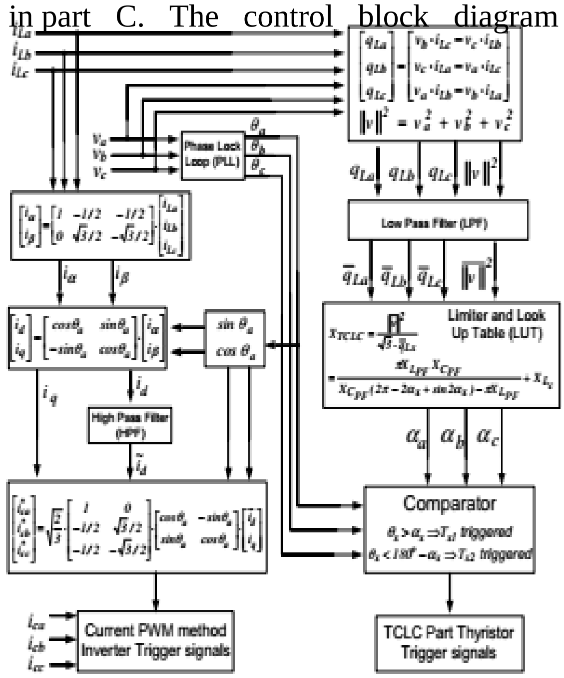


Fig. 5. The control block diagram of TCLC- STATCOM

A.TCLC part control

Different with the traditional SVC control based on the traditional definition of reactive power [2]-[3], to improve its response time, the TCLC part control is based on the instantaneous pq theory [4]. The TCLC part is mainly used to compensate the reactive current with the controllable TCLC part impedance inverter voltage invx≈0V , XTCLC can be calculated with Ohm's law in terms of the RMS values of the load voltage (Vx) and the load reactive current (ILqx)

B.Active inverter part control

In the proposed control strategy, the instantaneous active and reactive current id-iq method [7] is implemented .The calculated icx* contains reactive power, unbalanced power, and current harmonic components. By controlling the compensating current icx to track its reference icx*, the active inverter part can compensate for the load harmonic currents and improve the reactive power compensation ability and dynamic performance of the TCLC part under different voltage conditions.

C.Response time of TCLC-STATCOM

The TCLC part has two back-to-back connected thyristors in each phase that are triggered alternately in every half cycle, so that the control period of the TCLC part is one cycle (0.02 s). However, the proposed TCLC-STATCOM structure connects the TCLC part in series with an instantaneous operated active inverter part, which can significantly improve its overall response time. With the proposed controller, the active inverter part can limit the compensating current icx to its reference value icx* via pulse width modulation (PWM) control, and the PWM control frequency is set to be 12.5 kHz.

ARTIFICIAL NEURAL NETWORKS (ANN)

The ANNs are difficult to describe with a simple definition. Maybe the closest description would be a comparison with a black box having multiple inputs and multiple outputs which operates using a large number of mostly parallel connected simple arithmetic units. The most important thing to remember about all ANN methods is that they work best if they are dealing with non-linear dependence between the inputs and outputs

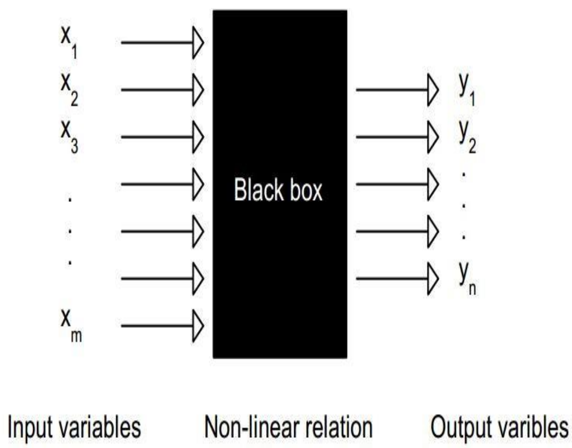


Fig.6 Neural network as a black-box featuring the non-linear relationship

ANNs can be employed to describe or to find linear relationship as well, but the final result might often be worse than that if using another simpler standard statistical techniques. Due to the fact that at the beginning of experiments we often do not know whether the responses are related to the inputs in a linear on in a nonlinear way, a good advice is to try always some standard statistical technique for interpreting the data parallel to the use of ANNs.

Basic concepts of ANNs

Artificial neuron is supposed to mimic the action of a biological neuron, i.e., to accept many different signals, xi, from many neighboring neurons and to process them in a pre-defined simple way. Depending on the outcome of this processing, the neuron j decides either to fire an output signal yj or not. The output signal (if it is triggered) can be either 0 or 1, or can have any real value between 0 and 1 (Fig. 11) depending on whether we are dealing with 'binary' or with 'real valued' artificial neurons, respectively.

Mainly from the historical point of view the function which calculates the output from the m-dimensional input vector X, f(X), is regarded as being composed of two parts. The first part evaluates the so called 'net input', Net, while the second one 'transfers' the net input Net in a non-linear manner to the output value y.

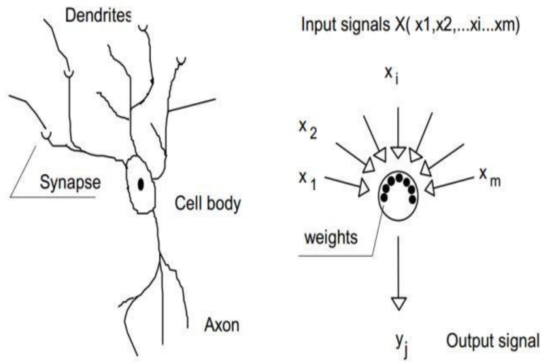


Fig. 7 Comparison between the biological and artificial neuron

The weights wji in the artificial neurons are the analogues to the real neural synapse strengths between the axons firing the signals and the dendrites receiving those signals (Figure 5). Each synapse strength between an axon and a dendrite (and, therefore, each weight) decides what proportion of the incoming signal is transmitted into the neurons body.

Some possible forms for the transfer function are plotted in Figure 6. It is important to understand that the form of the transfer function, once it is chosen, is used for all neurons in the network, regardless of where they are placed or how they are connected with other neurons. What changes during the learning or training is not the function, but the weights and the function parameters that control the position of the threshold value, qj , and the slope of the transfer function aj.(eqs. /2/, /3/).

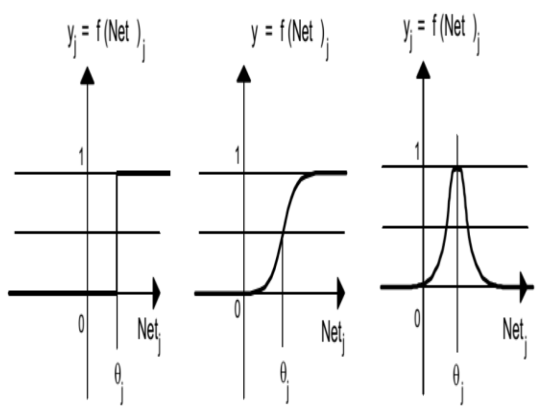


Fig. 8 Three different transfer functions: a threshold (a) a sigmoidal (b) a radial function (c)The parameter qj in all three functions decides the Netj value

Artificial neural networks (ANNs) can be composed of different number of neurons. In chemical applications, the sizes of ANNs, i.e., the number of neurons, are ranging from tens of thousands to only as little as less than ten (1-3). The neurons in ANNs can be all put into one layer or two, three or even more layers of neurons can be formed. Figure 8 show us the difference between the one and multilayer ANN structure.

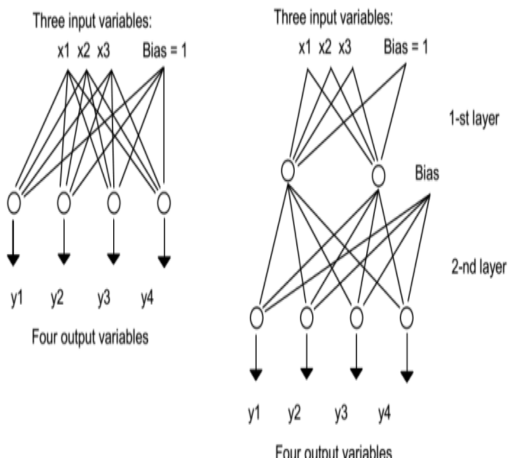


Fig. 9 One-layer (left) and two-layer (right) ANNs

In Figure 8 the one-layer network has four neurons (sometimes called nodes), each having four weights. Altogether there are 16 weights in this one- layer ANN. Each of four neurons accept all input signals plus the additional input from the bias which is always equal to one. The fact, that the input is equal to 1, however, does not prevent the weights leading from the bias towards the nodes to be changed! The two-layer ANN (Fig. 8,right) has six neurons (nodes): two in the first layer and four in the second or output layer. Again, all neurons in one layer obtain all signals that are coming from the layer above. The two-layer network has (4 x 2) + (3x 4) =20 weights: 8 in the first and 12 in the second layer. It is understood that the input signals are normalized between 0 and 1

VI. SIMULATION RESULTS

In this section, the simulation results among traditional STATCOM, C-STATCOM, and the proposed TCLC-STATCOM are discussed and compared. The detailed simulation results are summarized in Table II.

TABLE II

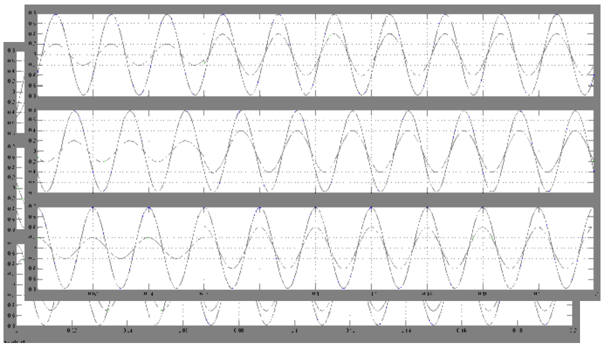
SIMULATION RESULTS FOR INDUCTIVE AND CAPACITIVE REACTIVE POWER COMPENSATION OF TRADITIONAL STATCOM, C-STATCOM AND TCLC-STATCOM

Loading Type	Without and With STATCOM Comp.	i_{sx}(A)	*DPF*	$THDi_{sx}$ (%)	V_{DC}(V)
Case A: inductive and light loading	Before Comp.	6.50	0.83	0.01	--
	Trad. STATCOM	5.55	1.00	7.22	300
	C-STATCOM	5.48	1.00	2.01	80
	Hybrid STATCOM	5.48	1.00	1.98	50
Case B: inductive and heavy loading	Before Comp.	8.40	0.69	0.01	--
	Trad. STATCOM	5.95	1.00	6.55	300
	C-STATCOM	6.30	0.85	17.5	50
	C-STATCOM	5.90	0.98	7.02	300
	Hybrid STATCOM	5.89	1.00	2.10	50
Case C: capacitive loading	Before Comp.	4.34	0.78	0.01	--
	Trad. STATCOM	3.67	1.00	7.61	250
	C-STATCOM	7.10	0.57	23.5	50
	C-STATCOM	5.02	0.99	10.6	500
	Hybrid STATCOM	3.41	1.00	3.01	50

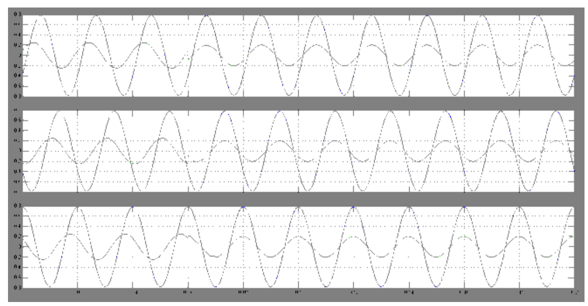
**Shaded areas indicate unsatisfactory results.*

A.Inductive and light loading When the loading is inductive and light,traditional STATCOM requires a high DC-link voltage (Vdc>·V2 −LL =269V, Vdc=300V) for compensation. After compensation, the source current isx is reduced to 5.55A from 6.50A and the source-side displacement power factor (DPF) becomes unity from 0.83.

B.Inductive and heavy loading To compensate for the inductive and heavyloading, traditional STATCOM still requires a high DC-link voltage of Vdc=300V for compensation Traditional STATCOM can obtain acceptable results (DPF = 1.00 and THDisx = 6.55%).



a)



c)

b)

Fig. 10.Dynamic compensation waveforms ofvx andisx by applying TCLC-STATCOM under (a) inductive load; (b) capacitive load; and (c) changing from capacitive load to inductive load

C.Capacitive loading

When the loading is capacitive, with Vdc=250V (Vdc< −LL =·V269V2), the compensation results of traditional STATCOM are acceptable, in which the DPF and THDisx are compensated to unity and 7.61%. The isx is also reduced to 3.67A from 4.34A after compensation

D.Dynamic response of TCLC-STATCOM

Fig. 11 shows the dynamic performance of TCLC-STATCOM for different loadings compensation

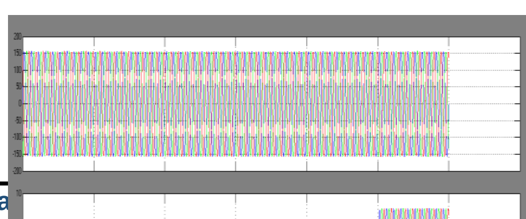
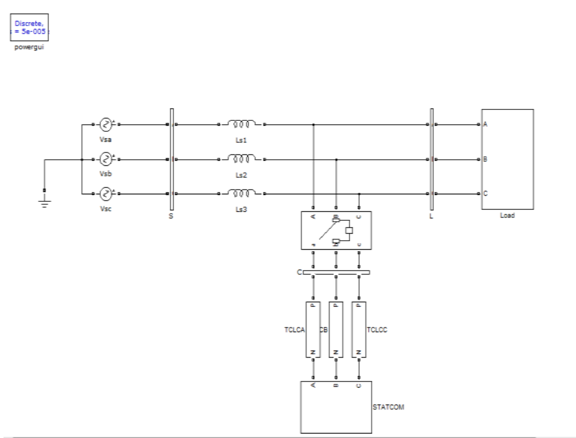


Fig. 11. Dynamic compensation waveforms of load voltage, source current, and load and source reactive powers by applying TCLC-STATCOM under different loadings cases.

Meanwhile, the fundamental reactive power is compensated to around zero even during the transient time. In practical situations, the load reactive power seldom suddenly changes from capacitive to inductive or vice versa, and thus TCLC- STATCOM can obtain good dynamic performance.



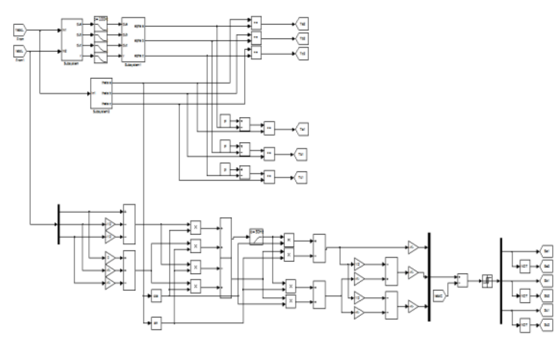
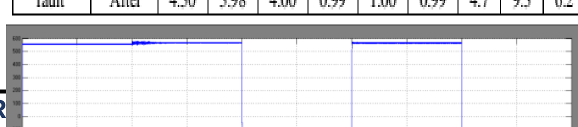


Fig 12 Block diagram of simulation Fig 12 Block diagram of control circuit

TABLE III
EXPERIMENTAL COMPENSATION RESULTS BY TCLC-STATCOM (VDC= 50V) UNDER DIFFERENT SYSTEM AND LOADING SITUATIONS

Different Situations	Comp.	i_{sx}(A)			DPF			$THDi_{sx}$ (%)		
		A	B	C	A	B	C	A	B	C
Inductive load	Before	7.13	7.14	7.34	0.69	0.70	0.70	1.1	1.2	1.2
	After	4.79	4.97	4.95	1.00	1.00	1.00	3.5	3.3	3.3
Capacitive load	Before	3.60	3.63	3.65	0.65	0.64	0.64	3.1	2.9	2.8
	After	2.92	2.80	2.85	1.00	1.00	1.00	5.4	5.4	5.2
Unbalanced loads	Before	4.80	3.83	5.74	0.36	0.69	0.64	2.0	1.4	1.2
	After	2.94	2.79	2.86	1.00	1.00	1.00	5.9	8.7	8.1
Voltage fault	Before	5.57	4.18	7.06	0.67	0.38	0.87	2.3	2.5	1.6
	After	4.30	3.98	4.00	0.99	1.00	0.99	4.7	9.3	6.2



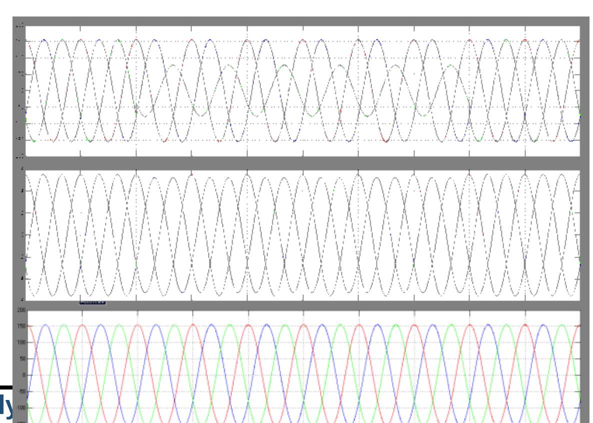
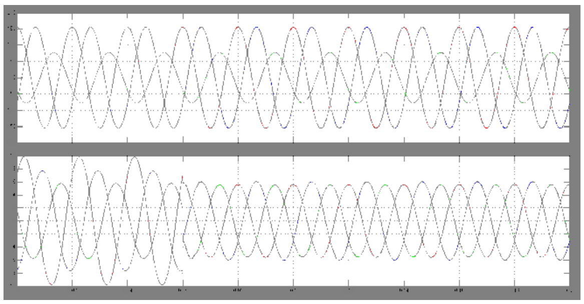


Fig. 14.Dynamic reactive power compensation phase aby applying TCLC-STATCOM

Fig. 15.Dynamic compensation disx waveforms Of by applying TCLC STATCOM unbalanced loads



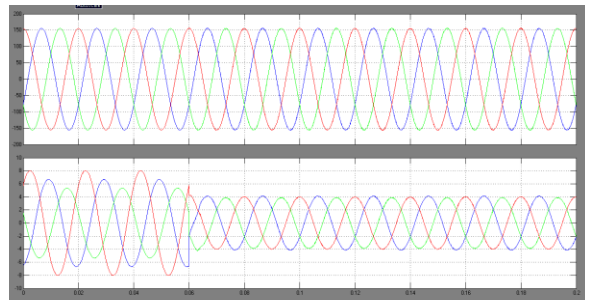


Fig. 16.Dynamic compensation waveforms of vxandisxby applyingTCLCSTATCOM during voltage dip under voltage fault condition

Fig. 17.Dynamic compensation waveforms of vxandisxby applying TCLCSTATCOM

CONCLUSIONS

The circuit configuration of TCLC- STATCOM is proposed in this paper. A TCLC static synchronous compensator (TCLC-STATCOM) in a three-phase power transmission system that has a wide compensation range and low DC-link voltage is proposed in this paper**.** This is achieved by "Back propagation algorithm" and this makes ANN a learning algorithm because by learning from the errors, the model is improved. Key advantages of neural Networks. Compared with traditional STATCOM and C-STATCOM the system configuration and V-I characteristic of the TCLC-STATCOM are analyzed in this paper. In addition, its parameter design method is proposed on the basis of consideration of the reactive power compensation range and prevention of a potential resonance problem. Moreover, the control strategy of the TCLC-STATCOM is developed under different voltage and current conditions. By using the simulation results we can analyze the wide compensation range and low DC-link voltage characteristics with good dynamic performance of the TCLC-STATCOM

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