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COORDINATED CONTROL OF A BACK-TO-BACK HVDC LINK

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ABSTRACT

THIS THESIS WILL PRESENT THE MATHEMATICAL MODEL, CONTROLLER DESIGN, SIMULATION, ANALYSIS OF A COMPLETE BACK-TO-BACK VSC HVDC SYSTEM. THERE WILL BE TWO STATIONS OF VOLTAGE SOURCE CONVERTER (VSC) LOCATED BACK-TO-BACK. ONE STATION SHALL ACT AS A RECTIFIER AND ANOTHER ONE WILL BE THE INVERTER. THIS WILL ALLOW POWER TRANSFER FROM ONE STATION (RECTIFIER) TO OTHER (INVERTER) THROUGH A DC LINK. A BACK-TO-BACK VSC HVDC HAS THE ADVANTAGES COMPARE TO THE AC TRANSMISSION BECAUSE IT CAN ALLOW POWER TRANSFER WITHOUT HAVING TO SYNCHRONIZE BOTH OF THE STATION OR NETWORKS. IN ORDER TO COMPLETE A BACK-TO-BACK VSC HVDC SYSTEM, IT WILL REQUIRE A D-Q CURRENT CONTROLLER, DC VOLTAGE CONTROLLER, ACTIVE/REACTIVE POWER CONTROLLER AND DC POWER (DC CURRENT CONTROLLER). A SIMULATION AND ANALYSIS SHALL BE EXECUTED FOR EACH OF THE CONTROLLER AND RESPONSE OF VOLTAGE AND CURRENT IN A COMPLETE SYSTEM. THE SIMULATION RESULT WILL SHOW THE DYNAMIC CONTROL OF THE RECTIFIER AND INVERTER IS ACHIEVED WITH FAST RESPONSE.

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SYMBOL AND ABBREVIATION

HVDC	-	HIGH VOLTAGE DIRECT CURRENT
UHVDC	-	ULTRA-HIGH VOLTAGE DIRECT CURRENT
AC	-	ALTERNATING CURRENT
DC	-	DIRECT CURRENT
IGBT	-	INSULATED-GATE BIPOLAR TRANSISTOR
PLL	-	PHASE LOCKED LOOP
LCC	-	LINE-COMMUTATED CURRENT-SOURCE CONVERTER
SCC	-	SELF-COMMUTATED VOLTAGE-SOURCE CONVERTER
PWM	-	PULSE WIDTH MODULATION
EMI	-	ELECTROMAGNETIC INTERFERENCE
P	-	ACTIVE POWER
Q	-	REACTIVE POWER
ABC	-	THREE PHASE
R	-	RESISTANCE
L	-	INDUCTANCE
C	-	CAPACITANCE
P_{REF}	-	ACTIVE POWER REFERENCE VALUE
Q_{REF}	-	REACTIVE POWER REFERENCE VALUE
I_{DREF}	-	D-AXIS CURRENT REFERENCE VALUE
I_{QREF}	-	Q-AXIS CURRENT REFERENCE VALUE
α	-	ALPHA
β	-	BETA
V_d	-	D-AXIS VOLTAGE
V_q	-	Q-AXIS VOLTAGE
V_{td}	-	D-AXIS RECTIFIER TERMINAL VOLTAGE
V_{tq}	-	Q-AXIS RECTIFIER TERMINAL VOLTAGE

I_d	-	D-AXIS CURRENT
I_q	-	Q-AXIS CURRENT
$\hat{\theta}$	-	VOLTAGE ANGLE
f_s	-	SWITCHING FREQUENCY
f	-	FREQUENCY
T_s	-	SWITCHING PERIOD
V_{dc}	-	DIRECT CURRENT VOLTAGE
V_s	-	SUPPLY VOLTAGE
V_{sabc}	-	THREE PHASE SUPPLY VOLTAGE
V_a	-	PHASE A VOLTAGE
V_b	-	PHASE B VOLTAGE
V_c	-	PHASE C VOLTAGE
I_{sabc}	-	THREE PHASE SUPPLY CURRENT
V_{tabc}	-	RECTIFIER TERMINAL VOLTAGE
\hat{V}_{ac}	-	PEAK ALTERNATING-CURRENT VOLTAGE VALUE
\hat{I}_{ac}	-	PEAK ALTERNATING-CURRENT CURRENT VALUE
ξ	-	DAMPING FACTOR
ω_n	-	NATURAL FREQUENCY
K_p	-	PROPORTIONAL GAIN
K_i	-	INTEGRAL GAIN
τ	-	TIME CONSTANT
G(S)	-	TRANSFER FUNCTION

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

THE HIGH VOLTAGE DIRECT CURRENT (HVDC) SYSTEM IS FIRST TIME COMMISSIONED IN GOTLAND IN 1954. SINCE THEN, THE HVDC TRANSMISSION SYSTEM BECOMES MORE IMPORTANT TECHNOLOGY ESPECIALLY FOR LONG DISTANCE TRANSMISSION AND IN THE INTERCONNECTED POWER SYSTEM THAT HAS DIFFERENT FREQUENCY. THE HVDC LINK IS ABLE TO OVERCOME THE LIMITATIONS OF AC SYSTEM SUCH AS NO LIMIT FOR THE TRANSMISSION CABLE LENGTH FROM IMPEDANCE, PHASE ANGLE, FREQUENCY OR VOLTAGE FLUCTUATIONS, LOWER SHORT CIRCUIT CURRENT AND IMPROVE THE AC SYSTEM'S CONTROLLABILITY AND STABILITY.

THERE ARE FEW TOPOLOGY OR TYPES OF HVDC SCHEMES AND ONE OF IT IS THE BATTERY BACK CONVERTER. FOR THIS TYPE OF CONVERTER, THE RECTIFIER AND INVERTER ARE LOCATED IN THE SAME AREA AND USUALLY IN THE SAME BUILDING. THIS WILL HELP TO LIMITS THE CONVERSION LOSS AND INCREASE THE EFFICIENCY. THE MAIN APPLICATIONS OF THIS TYPE OF CONVERTER ARE TO INTERCONNECT AC SYSTEM WITH DIFFERENT FREQUENCIES (E.G: 50 AND 60HZ). IN AC NETWORK SYSTEM, IT IS NOT POSSIBLE TO CONNECT THE TWO SYSTEM WITH DIFFERENT FREQUENCY. THEREFORE A VOLTAGE SOURCE CONVERTER (VSC) IS USED IN THE HVDC SYSTEM TO CONTROL THE POWER FLOW BETWEEN TWO AC NETWORKS THROUGH THE DC LINK. THE VSC IS CONSIDERED A NEW TECHNOLOGY WHICH USES IGBT AS IT SEMICONDUCTOR SWITCHING COMPONENT, REPLACING THE THYRISTOR WHICH IS USED IN THE 'CLASSIC' HVDC. THE IGBT HAS THE CAPABILITY TO TURN-ON AND TURN-OFF WHILE THYRISTOR ONLY HAS THE CAPABILITY TO TURN-ON. WITH THE SWITCHING METHOD BECOME MORE COMPLEX

CONTROLLER TO GENERATE SIGNAL MODULATION ALSO AFFECTED. A GOOD DESIGN OF C PROVIDE A COORDINATED CONTROL OF HVDC LINK WHICH CAN HELP TO ENSURES F INTERCONNECTION AMONG THE CONTROLLABLE DEVICES.

THIS PROJECT WILL FOCUS ON THE CONTROL COORDINATION OF BACK-TO-BACK H USING A MATLAB SIMULINK SOFTWARE. A MATLAB SIMPOWERSYSTEMS TOOLBOX, PROVIDE MATLAB SIMULINK SOFTWARE WILL BE USED TO DEVELOP THE POWER CONVERTER AND CONTROL THE SIMULATION WILL SHOW HOW IT WILL RESPOND TO THE MODULATION SIGNAL GENERATED BY THE CONTROLLERS. THE RESULT OF THE SIMULATIONS WILL HELP TO IMPROVE THE SYSTEM DYNAMICS AND IMPROVE THE TRANSFER CAPACITY.

1.2 PROBLEM STATEMENT

HVDC SYSTEM IS GETTING MORE IMPORTANT IN POWER TRANSMISSION SYSTEM TECHNOLOGY DUE TO THE ADVANTAGES COMPARE TO THE AC TRANSMISSION SYSTEM. THE HVDC START WITH THE INVENTION OF A MERCURY-ARC RECTIFIER WHICH IS USED IN THE LINE-COMMUTATED CURRENT CONVERTER. THE MERCURY-ARC RECTIFIER IS THEN REPLACED BY THE THYRISTOR VALVES WHICH IS THE NEXT DEVELOPMENT IN HVDC SYSTEM. INNOVATION IN ALMOST EVERY AREA OF HVDC SYSTEM HAVE BEEN CONSTANTLY ADDING TO IMPROVE THE RELIABILITY OF THE SYSTEM AND PROVIDE BENEFIT TO USERS. RECENTLY THE HVDC TECHNOLOGY BECOMES MORE EXPAND THE USE OF INSULATED GATE BIPOLAR TRANSISTOR (IGBT) IN SELF-COMMUTATED VOLTAGE SOURCE CONVERTER (VSC). THE MAIN CHARACTERISTICS OF VSC ARE COMPACT DESIGN, FOUR QUADRANT OPERATION, LOW HIGH LOSSES. THE VSC WILL CREATE MORE DYNAMICS FOR BETTER POWER QUALITY SYSTEM

IS ANOTHER PROBLEM OCCUR. THE IGBT SWITCHING FREQUENCY IS MUCH FASTER (>100000) COMPARE TO THE THYRISTOR SWITCHING FREQUENCY AROUND 50-60HZ. THIS WILL REQUIRE A NEW POWER CONVERTER AND CONTROL SYSTEM OF SIGNAL MODULATION GENERATION. THIS RESEARCH IS EXPECTED TO OVERCOME THE PROBLEM BY DEVELOPING THE COORDINATED CONTROL OF BACK-TO-BACK HVDC LINK BY USING MATLAB SIMULINK SOFTWARE.

1.3 AIM

- TO DEVELOP A COORDINATED CONTROL OF BACK-TO-BACK HVDC LINK USING MATLAB SIMULINK SOFTWARE.

1.4 RESEARCH OBJECTIVES

THE SCOPES OF THIS RESEARCH ARE AS FOLLOWS:

1. TO DESIGN VSC 1 AS CONSTANT DC SOURCE.
2. TO DESIGN VSC 2 AS CONSTANT DC SOURCE PLUS AN EXTERNAL DC CABLE CURRENT LOOP.
3. TO ESTABLISH POWER FLOW THROUGH THE HVDC LINK AND ANALYZE THE RESULT.

1.5 RESEARCH METHODOLOGY

THERE ARE FEW STEPS OF METHODOLOGY THAT WILL BE USED IN THIS PROJECT. THE IS TO MODEL THE POWER SYSTEM AND DETERMINE THE TRANSFER FUNCTION OF EACH COMPONENT OF THE HVDC SYSTEM. THE MODEL SHOULD BE KEPT AS SIMPLE AS POSSIBLE WHILE STILL CAPABLE OF REPRESENTING AN IMPORTANT ELEMENT OF THE SYSTEM. THERE IS TWO MAIN BLOCKS OF A POWER CONVERTER VSC1 (VSC FOR NETWORK 1) AND VSC2 (VSC FOR NETWORK 2).

THE VSC1 DESIGN STARTS BY DEVELOPING THE AC CURRENT CONTROLLER. BASED ON CLASSICAL CONTROL SYSTEM DESIGN TECHNIQUE, THE CONTROL LOOP, AND CONTROL PARAMETERS ARE DETERMINED. THE CURRENT CONTROLLER SHOULD BE ABLE TO RESPOND TO AN ACTIVE POWER DEMAND. A SUITABLE CURRENTS VALUE WILL BE INJECTED INTO THE AC GRID TO MEET THE POWER RESPONSE. THE DESIGNED CONTROLLER ALSO SHALL BE ABLE TO BE USED IN THE D-Q FRAME.

THE AC CURRENT CONTROLLER IS THEN SHALL BE ENHANCED BY INCLUDING THE PHASE LOCKED LOOP (PLL) FOR THE PURPOSE OF GRID SYNCHRONIZATION. A D-Q PLL IS CHOSEN TO BE USED IN THIS PROJECT DESIGN BECAUSE IT IS THE SIMPLEST CHOICE AVAILABLE. ONCE THE DESIGN COMPLETE AT THIS STAGE, THE POWER CONVERTER SHOULD BE ABLE TO CONTROL THE AC GRID ACTIVE POWER AT DESIRED VALUE.

THE COMPLETED MODEL ABOVE IS THEN WILL BE EXTENDED WITH DC VOLTAGE CONTROLLER. THIS IS THE END PART OF VSC1. THE DC VOLTAGE CONTROLLER SHALL BE ABLE TO CONTROL DC VOLTAGE AT A CONSTANT VALUE EVEN THOUGH THE LOAD RESISTOR VALUE IS CHANGE.

AFTER COMPLETE THE VSC1 DESIGN PART, THE VSC2 DESIGN WILL START WITH DC CURRENT CONTROLLER LOOP. THE FUNCTION OF THE CONTROL LOOP IS TO CONTROL CURRENT THAT FLOW THROUGH THE DC LINK.

HENCE CONTROL THE POWER TRANSMITTED THROUGH BACK-TO-BACK LINK SINCE THE CURRENT RELATION IS PROPORTIONAL. IN THE DC CURRENT LOOP, THERE WILL BE DC VOLTAGE AS THE THE CURRENT CONTROLLER OUTPUT WILL PROVIDE A REFERENCE VOLTAGE FOR THE DC VOLTAGE LOOP. DURING DESIGN THIS CONTROLLER, THE VSC1 WILL BE CONSIDERED AS AN IDEAL VOLTAGE SOURCE TO THE HVDC CABLE FOR DESIGN SIMPLICITY.

ONCE THE VSC1 AND VSC2 DESIGN ARE COMPLETED, THE MODEL OF FULLY CONTROLLED BACK-TO-BACK HVDC SYSTEM WILL BE IMPLEMENTED. FINALLY, THE PERFORMANCE OF THE SYSTEM WILL BE EXAMINED AND ANALYZE BY SIMULATION USING MATLAB SIMULINK. THE SIMULATION RESULTS WILL SHOW THE RESPONSE OF DC AND AC CURRENT, VOLTAGE AND POWER WHEN THE DC CURRENT REFERENCE IS CHANGED. THE SWITCHING VERSION OF THE FULL BACK-TO-BACK HVDC SYSTEM WILL BE IMPLEMENTED USING THE SAME CONTROLLER THAT HAVE BEEN DESIGNED.

1.6 SYSTEM DELIVERABLES

THIS PROJECT WILL DEVELOP THE CONTROL SYSTEM MODEL OF BACK-TO-BACK HVDC LINK. THE CONTROL PARAMETER SHALL BE DETERMINED USING THE CLASSICAL CONTROL SYSTEM DESIGN TECHNIQUE. THIS PROJECT WILL PRESENT THE SIMULATION RESULT OF THE DESIGN AND EVALUATION OF THE PROPOSED CONTROL SYSTEM OF BACK-TO-BACK HVDC LINK. THEN, THE SIMULATION RESULT WILL BE DISCUSSED AND ANALYZE.

CHAPTER 2

LITERATURE REVIEW

2.1 AN OVERVIEW OF HVDC SYSTEM

A HIGH VOLTAGE DIRECT CURRENT (HVDC) TECHNOLOGIES ARE KEEP DEVELOPING OVER TIME TO TIME. THE HVDC TECHNOLOGIES ARE STARTED WITH SO CALLED HVDC “CLASSIC” USING THYRISTOR AS ITS SWITCHING COMPONENT. IT ONLY HAS TURN-ON CAPABILITY WHICH HAS SOME DISADVANTAGES. THUS, THE CLASSIC HVDC IS ALSO KNOWN AS LINE-COMMUTATED CURRENT SOURCE CONVERTER (LCC/ CSC) [11]. THE HVDC TECHNOLOGIES ARE THEN HAS BEEN IMPROVED TO HVDC “PLUS” BY CHANGING THE SWITCHING COMPONENT FROM THYRISTOR TO IGBT BECAUSE OF THE CAPABILITY OF IGBT THAT CAN TURN-ON AND OFF. THIS TECHNOLOGY IS ALSO KNOWN AS COMMUTATED VOLTAGE-SOURCE CONVERTER (SCC/ VSC) [11].

THE FULLY CONTROLLED SEMICONDUCTOR DEVICES AVAILABLE TODAY FOR HIGH POWER CONVERTERS CAN BE BASED ON EITHER THYRISTOR OR TRANSISTOR TECHNOLOGY [1]:

ACRONYM	TYPE	FULL NAME
IGBT	TRANSISTOR	INSULATED GATE BIPOLAR TRANSISTOR
IEGT	TRANSISTOR	INJECTION ENHANCED GATE TRANSISTOR
GTO	THYRISTOR	GATE TURN-OFF THYRISTOR
IGCT	THYRISTOR	INTEGRATED GATE COMMUTATED THYRISTOR
GCT	THYRISTOR	GATE COMMUTATED TURN-OFF THYRISTOR

TABLE 2.1: SUMMARY OF FULLY CONTROLLED HIGH-POWER SEMICONDUCTOR DEVICES

TYPICALLY A VSC WHICH IS USE IGBT AS IT SWITCHING COMPONENT APPLY PULS
 MODULATION (PWM) OPERATING AT A HIGHER FREQUENCY THAN THE LINE FREQUEN
 CAUSE HIGHER SWITCHING LOSSES. FIGURE 2.1 INDICATES THE TYPICAL LOSSES DEP
 SWITCHING FREQUENCY [11]:

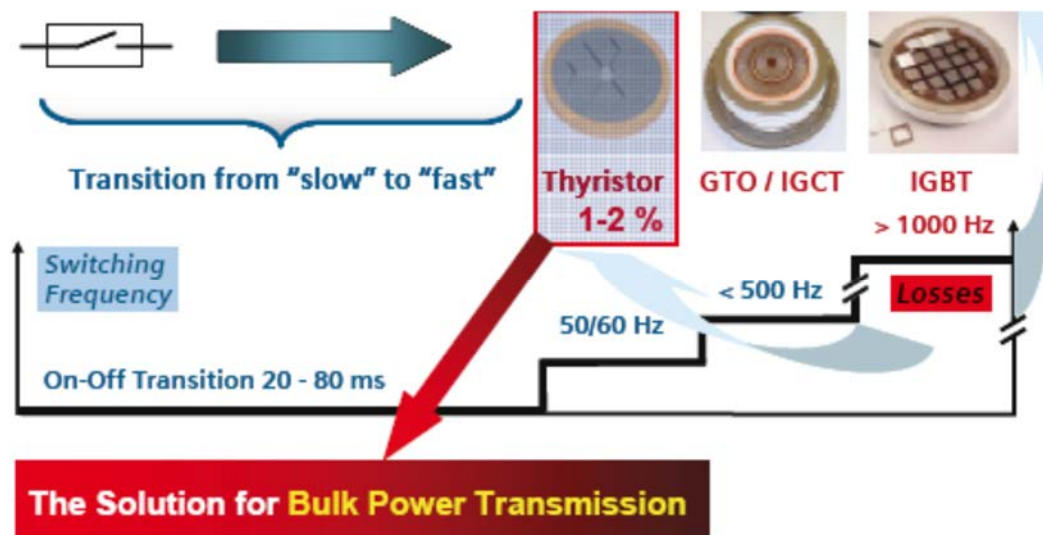


FIGURE 2.1: POWER ELECTRONICS FOR HVDC [11]

THE HIGH FREQUENCY OF PWM OPERATION IS DIRECTLY PROPORTIONAL TO THE
 LOSSES AND IT WILL REQUIRE A BETTER HEAT SINK DESIGN. THIS IS ONE OF THE MOST
 CHALLENGING ISSUES THAT NEED TO BE DEALT WITH IN VSC-BASED HIGH-POWER APPLI
 DISADVANTAGES IF USING VSC ARE THE ELECTROMAGNETIC COMPATIBILITY/EL
 INTERFERENCE (EMC/EMI), TRANSFORMER INSULATION STRESSES, AND HIGH-FREQUEN
 WHICH WILL REQUIRE ADDITIONAL FILTERS [1].

ALTHOUGH FACING MANY CHALLENGES, THE HVDC TECHNOLOGIES KEEP ON ORDER TO FULFILL THE POWER DEMAND THAT RISES EVERY YEAR. RISING DEMAND WIL POWER TO BE CARRIED OUT BY THE TRANSMISSION LINE. CURRENTLY, THE HIGHEST STATION IS THE ITAIPU POWER STATION WHICH IS RATED AT 12.6GW, 600KV. THE ITA STATION IS CONSIDERED AS THE ULTRA HIGH VOLTAGE DIRECT CURRENT (UHVDC) BE POWER RATING ABOVE 10GW. IN THE LATEST TECHNOLOGY, CHINA IS CURRENTLY BEIN THE POSSIBILITY OF USING THE UHVDC WITH VOLTAGE RATING IS 1,100KV FOR POWER TR OF 10 TO 13 GW PER LINE FOR DISTANCES OVER 2,000 KM [13]. NEW TECHNOLOGIES WIL NEW CHALLENGES IN TERM OF COMPONENTS, CONTROL, PROTECTION, CABLES AND SO

2.2 FUNDAMENTAL OF VSC-HVDC SYSTEM

CURRENTLY, THERE IS TWO TECHNOLOGY OF HVDC SYSTEM. FIRSTLY IS THE CSC-H THE OTHER ONE IS VSC-HVDC. FIGURE 2.2 SHOWS THE BASIC DIAGRAM OF CSC-HVDC FIGURE 2.3 SHOWS THE BASIC DIAGRAM OF VSC-HVDC [1][2]:

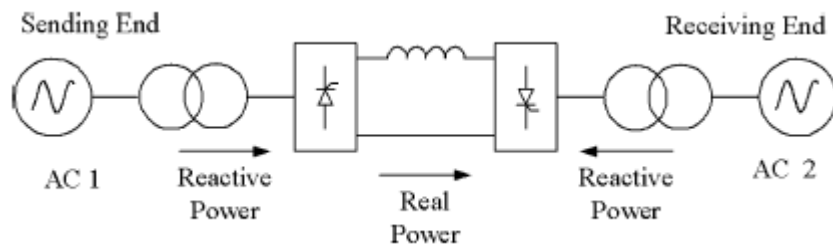


FIGURE 2.2: HVDC SYSTEM BASED ON CSC TECHNOLOGY WITH THYRISTORS

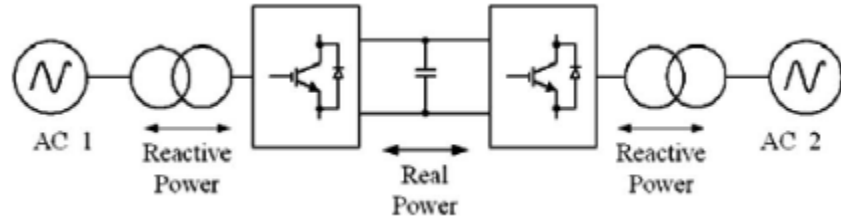


FIGURE 2.3: HVDC SYSTEM BASED ON VSC TECHNOLOGY WITH IGBTs

THE MAIN DIFFERENCE OF BOTH OF THE TECHNOLOGY IS THE SWITCHING COMPONENT. THYRISTOR IS USED IN CSC WHILE IGBT IS USED IN VSC TECHNOLOGY.

2.3 VSC-HVDC SYSTEM CONFIGURATION

VSC-HVDC CAN BE CONFIGURED TO SEVERAL TYPES OF TOPOLOGY/SCHEME SUCH AS BACK-TO-BACK HVDC SYSTEM, MONOPOLAR HVDC SYSTEM, BIPOLAR HVDC SYSTEM AND MULTITERMINAL HVDC SYSTEM [1][2][12].

2.3.1 BACK TO BACK VSC-HVDC SYSTEM

WITH THIS CONFIGURATIONS, THE CONVERTERS (RECTIFIER AND INVERTER) ARE LOCATED AT TWO DIFFERENT AC STATIONS. THIS CONFIGURATION IS USED TO INTERCONNECT TWO AC SYSTEM WHICH HAVE DIFFERENT FREQUENCY OR DIFFERENT FREQUENCY (ASYNCHRONOUS INTERCONNECTION). FIGURE 2.3 IS THE BASIC DIAGRAM FOR BACK-TO-BACK HVDC SYSTEM.

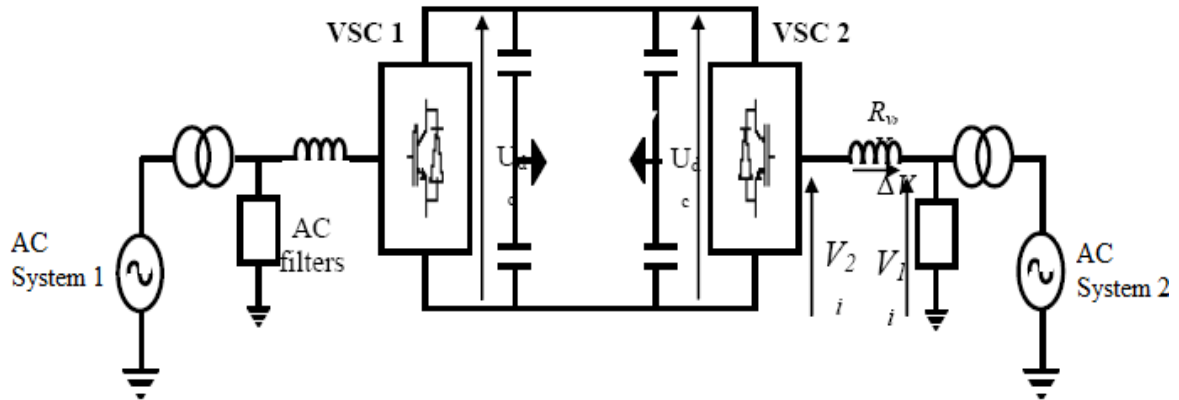


FIGURE 2.4: BASIC BACK-TO-BACK VSC HVDC SYSTEM

2.3.2 MONOPOLAR VSC-HVDC SYSTEM

THIS CONFIGURATION IS USUALLY USED FOR VERY LONG DISTANCES TRANSMISSION INVOLVED VERY LONG SEA CABLE TRANSMISSION WHICH WILL REQUIRE SUBMARINE CONNECTION. THE GROUND ELECTRODES ARE USE FOR THE RETURN PATH OF THE CURRENT.

2.3.3 BIPOLAR VSC-HVDC SYSTEM

A BIPOLAR HVDC SYSTEM IS A COMBINATION OF TWO MONOPOLAR SYSTEMS. IT IS USED IF THE POWER OR TRANSMISSION CAPACITY EXCEEDS THE SINGLE POLE CAPACITY. POWER CAPACITY WILL BE SPLIT INTO TWO POLES WITH EACH POLE COVER 50% OF THE TOTAL. THE ADVANTAGE OF THIS CONFIGURATION, IT IS STILL ABLE TO PROVIDE 50% OF POWER DURING THE MAINTENANCE OF ONE OF THE POLE.

2.3.4 MULTI-TERMINAL VSC-HVDC SYSTEM

THIS CONFIGURATION IS THE COMBINATION OF MORE THAN TWO SETS OF THE BL
THIS CONFIGURATION IS APPLIED IN A LARGE GRID WHICH CAN OFFER MORE ECON
TRANSMISSION LINE AND PROVIDE BETTER FLEXIBILITY IN POWER DISPATCH AND STA
AC SYSTEM [7].

2.4 CONTROLLER IN BACK TO BACK VSC-HVDC SYSTEM

THE CONTROLLER OF THE VSC-HVDC SYSTEM FOR CONVERTER 1 (RECTIFIER) AN
2 (INVERTER) CONTROLLER DESIGN ARE IDENTICAL BUT BOTH CONVERTER CON
COMMUNICATION BETWEEN THEM AND OPERATE INDEPENDENTLY. THERE IS FOUR MAI

A. CURRENT CONTROLLER (INNER LOOP)

THE CURRENT CONTROLLER IS THE INNER LOOP OF THE ACTIVE AND RE
CONTROLLER. THE INNER LOOP RESPONSE SHALL BE FASTER THAN THE OUTE
D-Q CURRENT COMPONENT TO CONTROL AC CURRENT IN CASE OF THE CHA
CURRENT THAT MAY CAUSE THE LOAD CHANGES OR FAULT. THE D-Q COMPON
ORDER PLANT AND BOTH ARE INDEPENDENTLY RELATED [3].

B. ACTIVE POWER CONTROLLER (OUTER LOOP)

THE ACTIVE POWER CONTROLLER IS USED TO KEEP THE POWER TRANSMITTI
LINK AT THE REFERENCE VALUE IN ORDER TO CONTROL THE ACTIVE POWER FLOW C
VOLTAGE LEVEL, THE ACTIVE POWER IS USED IN THE INNER CURRENT LOOP CON
[8].