Review Article   **Open Access**

Simulation of Power Converter for HVDC Transmission

Nader Barsoum* and Peridiana Kisam

Electrical and Electronics Engineering, Faculty of Engineering, University of Sabah, Kota Kinabalu, Malaysia

*Corresponding author: Nader Barsoum, University Malaysia Sabah, Malaysia, Tel: +6088320000; E-mail: nader@ums.edu.my

Abstract

A high voltage direct current (HVDC) is the technology to transmit electrical power over a long distance. HVDC system consists of power converter for converting AC power of the power station to DC power for transmission cable. A lower harmonic distortion and high power factor are the goals for this paper. A high power factor provides an efficient system with a low current draws into the electrical equipment and less power losses with improvement of voltage regulation within the equipment. In this paper, a three-phase system is designed using MATLAB SIMULINK software. A 22 kV AC source with step-up 22 kV/132 kV transformer is connected to the 6-pulse rectifier with LC filter and boost regulator is designed to obtain a 600 kV DC source. LC filter is used to eliminate the harmonics of DC signal while the boost regulator is used to increase the level of DC voltage. This research, therefore, investigates the harmonic distortion of voltage and current of DC signal. From the simulation result a total harmonic distortion THD obtained is less than 20% and up to 0.9 power factor.

Keywords: HVDC, LC filter, Boost regulator, THD, power factor

Introduction

This work is related to power electronics field where it is the integration of electrical power and the electronic devices. It involves the conversion of power such as changing voltage form from AC to DC and from DC to a higher value of DC voltage value; the aim is the improvement of efficiency and reliability since the power converter influence the efficiency and reliability of the system. Less efficient power converter cause a failure of the system. The design of power converter is improved in order to achieve high efficiency.

Power converter consists of rectifier which is the conversion of AC to DC and the converter which is the conversion of DC to DC. However, switch such as diodes and IGBT used in the power converter are non-linear devices. Non-linear devices create ripple in the signal by means of higher harmonic distortion and cause a non-unity power factor. Therefore, it creates imperfect output signal compare to the linear devices such as capacitor, resistor and inductor that have no harmonics contain in their signal [1]. In order to minimize the ripple of the output signal, a filter designed is one of the solutions.

A high voltage direct current (HVDC) connection is a technology that transmitting electrical power over a long distance of transmission cable. HVDC consists of three main parts namely, converting station, transmission cable, and inverting station [2]. Power converter circuit is used in the converting station from AC to DC. The AC voltage contains unbalanced system and the power converter side consists of harmonics due to the non-linear devices that leading to a less efficient system. The filtering scheme such as AC filter and DC filter can reduce the harmonics and at the same time a unity power factor can be achieved [3].

The harmonics in HVDC system can cause higher power loss, reduce electrical equipment lifespan and make the system collapse. In addition, it may cause the capacitor overheat and the instability of the transformer. A passive inductor capacitor (LC) filter and shunt active power filter can be designed in the system to eliminate harmonics [4]. In HVDC system, the DC voltage level can be increased by using a boost regulator from the converter station to feed the DC source into the transmitting cable.

Since, the HVDC technology is most implemented nowadays, it is important to provide an efficient system. In Malaysia, the HVDC system is already implemented between Malaysia and Thailand with monopolar connection types of 300 kV over 110 km distances and supplying 300 MW powers [5]. A reduced switch five stages power converter using a multicarrier PWM control schemes produce 23.83% of its THD [6]. Moreover, a simulation of 12-pulse converter based VSC system for HVDC presented a power factor of 0.994 and THD of 2.71% at DC voltage and 2.52% at DC current [7].

In this paper, implementation of rectifier is the most concern where it is improved in order to obtain less harmonics and high power factor. The three-phase AC line used is 22 kV of each phase and step-up to 132 kV using three-phase transformer. From the secondary side of transformer, the AC supplies the rectifier circuit to convert the AC into a DC signal. The produced DC signal is boosted using a boost regulator until reach 600 kV. The filtering system used is LC filter located between rectifier and the load. MATLAB SIMULINK software is used to construct the circuit model and analyze and simulate the response.

Methodology

MATLAB R2014a software is used to design and analyze this work. Figure 1 is the block diagram of this system. First of all, a 22 kV three-phase AC source connected to the 22 kV/132 kV three-phase step-up transformer. Then, the AC input source from secondary winding is connected into the three-phase 6-pulse uncontrolled diode rectifier where it is operated to convert the AC signal into the DC signal. However, the ripple is high at the rectifier side. Therefore, in order to reduce the ripple of the signal, an LC filter is connected between rectifier and load. The level of the rectified DC voltage increases up to 600 kV by using five stages of boost regulator circuit. The voltage and current meters are attached at both rectifier and boost output to measure the ripples of DC signal. Then both total harmonic distortion (THD) and power factor are analyzed using FFT analysis and measurement circuit of power factor.
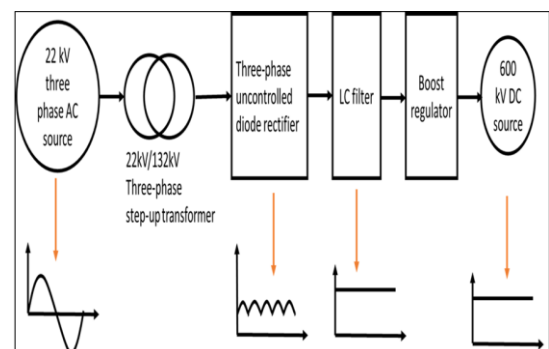

Figure 1: Block diagram of the simulation circuit

Circuit Design and Simulation

The three-phase 6-pulse diode rectifier is implemented to convert AC into DC signal as shown in figure 2. It is connected from the secondary side of the three-phase transformer. The DC voltage and DC current can be obtained from equation (2) and (3).
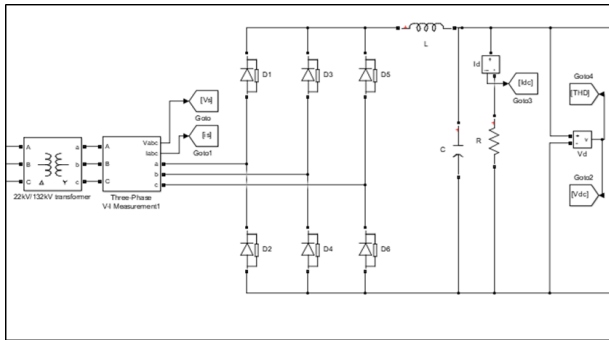

Figure 2: Three-phase 6-pulse diode rectifier

Base power, S = 300 MW
Input voltage, V = 22 kV

$$S = 3VI \qquad (1)$$

Input current,

$$I = \frac{300 * 10^6}{3 * 22 * 10^3} = 4545.45A$$

The ratio of three-phase transformer is: N=132 kV/22 kV = 6

Secondary current,

$$I_s = \frac{I}{N} = \frac{4545.45}{6} = 757.58A$$

Since the two windings of transformer are connected in delta-star, so the secondary current is multiple by square root 3.

Hence, I_s = 1312 A

The voltage at secondary winding is,

$$V_L = 132kV$$

DC voltage is calculated as,

$$V_d = 1.35 * V_L \qquad (2)$$
$$V_d = 1.35 * 132k = 178kV$$

DC current is calculated as,

$$I_d = \frac{Vd}{R} \qquad I_d = \frac{178k}{50k} = 3.56A \qquad (3)$$

Figure 4 and 5 shows the rectified voltage and rectified current of rectifier circuit where the three-phase AC source converted into DC signal. The rectified voltage measured is 163 kV and the rectified current is 3.25 A. Both measured value are not equal with the calculation due to loss produce by the non-linear devices, diode drops and the unstable ac source.

Inductor Capacitor (LC) filter is connected between the rectifier and the load as in figure 3 which is the purpose of reducing ripples of the DC signal. The LC circuit of figure 3 shows that the inductor is in series and the capacitor is in parallel with the load R. The value of LC is calculated as below.

Resonance frequency,

$$f_r = \frac{1}{(2*3.14*\sqrt{LC})} \qquad (4)$$

Since, this circuit has frequency of 50 Hz, the resonance frequency for LC filter must be less than 50 Hz [8]. By selecting LC value as L = 12.5 mH and C = 2.5 mF, the resonance frequency is,

$$= \frac{1}{(2*3.14*\sqrt{0.0125*0.0025})} = 28Hz$$

By using LC filter, the ripple of the signal can be reduced. The magnified rectified voltage is shown in figure 6 where the ripple of the DC waveform is calculated as:

$$\frac{1.6254 - 1.6253}{1.6254} = 0.000062 \; or \; 0.0062\%$$
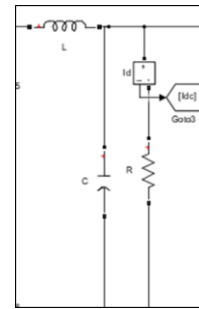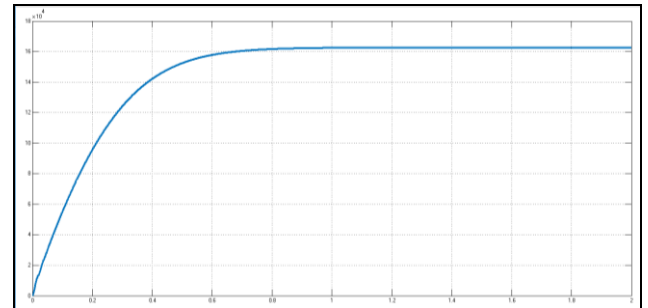

Figure 3: LC filter

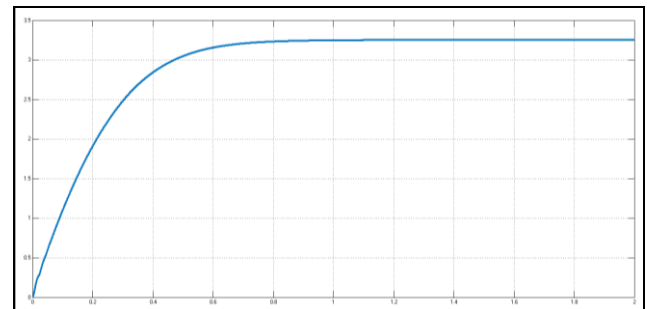Figure 4: Waveform of rectified voltage of 163 kV

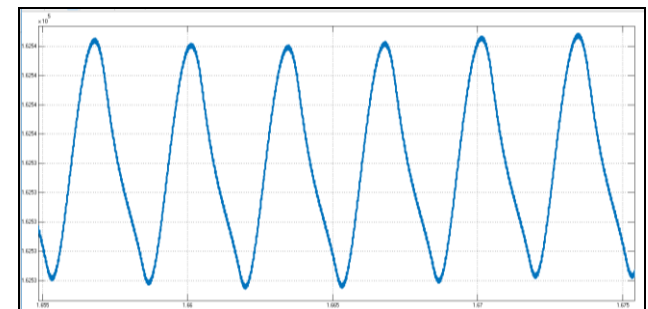Figure 5: Waveform of rectified current of 3.25 A

Figure 6: Waveform of magnified rectified voltage

The rectified DC voltage increases to 600 kV by using boost regulator circuit. Five stages of boost circuit are implemented as in figure 7. In this circuit, the used of MOSFET and diodes which is a non-linear devices produce harmonic distortion. A lower duty cycle is required to reduce the current flowing through the circuit. The value of parameters for boost circuit is selected according to the calculation in Table 1.
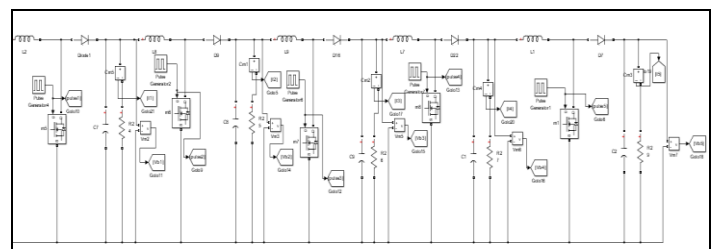

Figure 7: Five stages boost regulator circuit

Stage	$D=\dfrac{\frac{V_o}{V_{in}}-1}{\frac{V_o}{V_{in}}}$	V_{in} (kV)	V_{out} (kV)	I_{out} (A)	Ripple %
1	0.06	178	190	8.1	0.25
2	0.24	190	250	8.3	0.089
3	0.24	250	330	8.3	0.6
4	0.25	330	440	8.8	0.03
5	0.27	440	600	6.6	0.024

Table 1: Duty cycle for each stage of boost converter

Table 1 shows the calculation for each stage of boost circuit for estimated output voltage, current and ripple with the required duty cycle. It is including the requirement for lower duty cycle which is less than 0.5 for each stage to prevent less voltage drop and overheating. The input DC of 178 kV is from the rectification output. A 600 kV is achieved at the last stage of boost circuit. Table 2 is the calculation of parameters for boost circuit at each stage.

Table 2 shows the calculated value of resistor, inductor and capacitor at each stage of boost circuit. The value of each parameter can be obtained according to the formula of equation (5) and (6). The ripple is assumed to be 0.000062 as it calculated from figure 6.

$$L = \frac{RD(1-D)^2}{2f} \quad (5)$$

$$Ripple = \frac{D}{RCf} \quad (6)$$

D	f_s (kHz)	Ripple (%)	R (k Ω)	L (m H)	C (µ F)
0.06	25	0.062	23	24.4	1.683
0.24	25	0.062	30	83.2	5.161
0.24	25	0.062	40	110.9	3.871
0.25	25	0.062	50	140.6	3.226
0.27	25	0.062	80	230.2	2.177

Table 2: Boost parameter value

Table 3 shows the period of switching ON and OFF for the MOSFET. Higher switching frequencies of the MOSFET are applying to reduce the ripple at the output voltage. A higher frequency will make the voltage charging and discharging times at the capacitor become shorten. The charging voltage is t_{on} and the discharging voltage is t_{off}.

Stage	t_{on}(s)	t_{off}(s)
1	0.06/25000 = 2.4µ	40µ - 2.4µ = 37.6µ
2	0.24/25000 = 9.6µ	40µ - 9.6µ = 30.4µ
3	0.24/25000 = 9.6µ	40µ - 9.6µ = 30.4µ
4	0.25/25000 = 10µ	40µ - 10µ = 30µ
5	0.27/25000 = 10.8 µ	40µ - 10.8µ = 29.2µ

Table 3: t_{on} and t_{off} of boost circuit

Figures 8 - 15 show the response of output voltage and output current for the first 2 and last stages of boost converter. The ripple of output voltage is calculated for each stage.
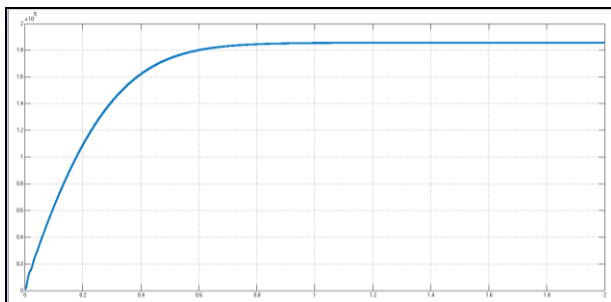

Figure 8: Waveform of output voltage for stage 1 boost converter

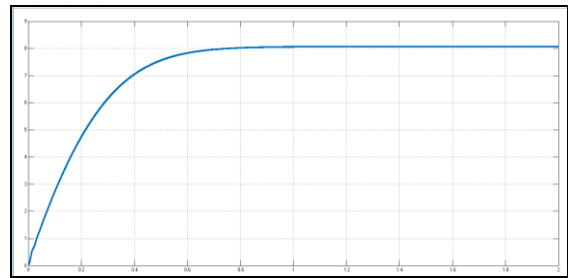The measured output voltage is 190 kV.

Figure 9: Waveform of output current for stage 1 boost converter
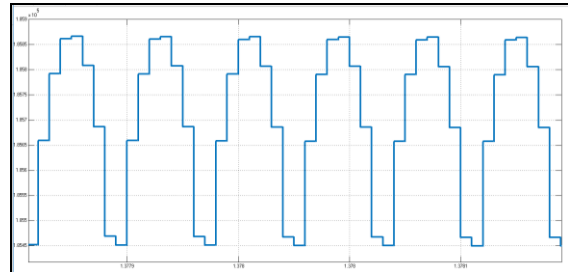
The measured output current is 8.1 A.

Figure 10: Waveform of magnified output voltage for stage 1

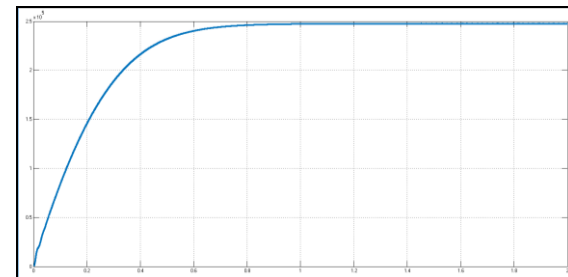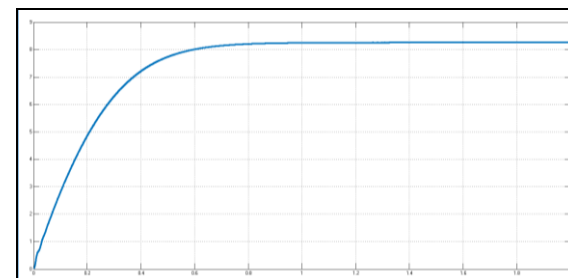The ripple is: $\dfrac{1.8587-1.854}{1.8587} = 0.0025 \ or \ 0.25\%$.

Figure 11: Waveform of output voltage for stage 2 boost converter

The measured output voltage is 250 kV.

Figure 12: Waveform of output current for stage 2 boost converter
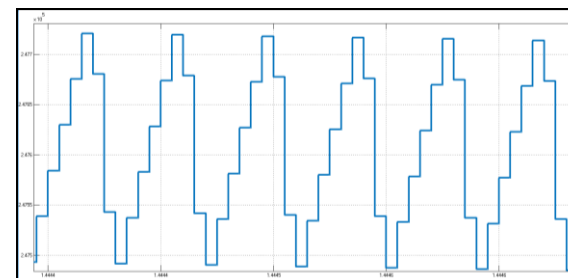
The measured output current is 8.3 A.

Figure 13: Waveform of magnified output voltage for stage 2

The ripple is: $\dfrac{2.4772-2.475}{2.4772} = 0.000089 \ or \ 0.089\%$
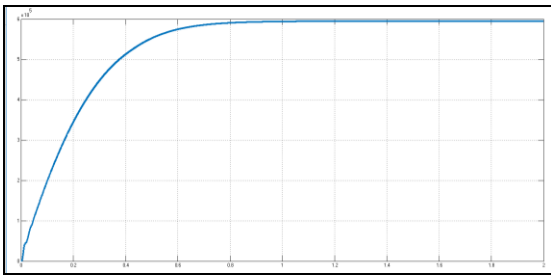
Figure 14: Waveform of output voltage for stage 5 boost converter

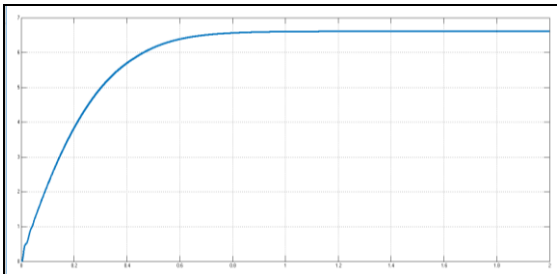The measured output voltage is 600 kV.

Figure 15: Waveform of output current for stage 5 boost converter

The measured output current is 6.6 A.

Performance Test

The investigation and measurement of the simulation design is taken in term of total harmonic distortion and power factor. The total harmonic distortion for the rectified the whole system is measured by using the Fast Fourier Transform (FFT) analysis that provided in MATLAB software.
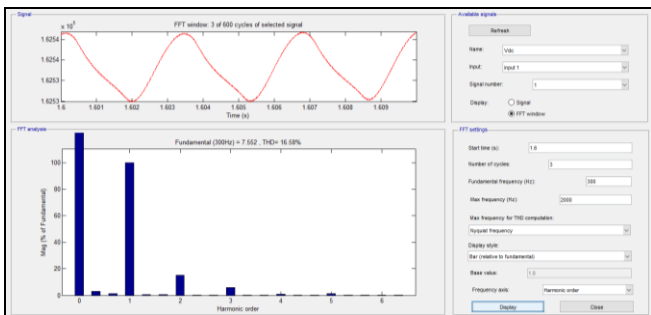

Figure 16: Total harmonic distortion for rectified voltage

Figure 16 shows the total harmonic distortion relative to fundamental frequency of 300 Hz. The THD is 16.58%. The figure shows the magnitude of the fundamental and the harmonic order.
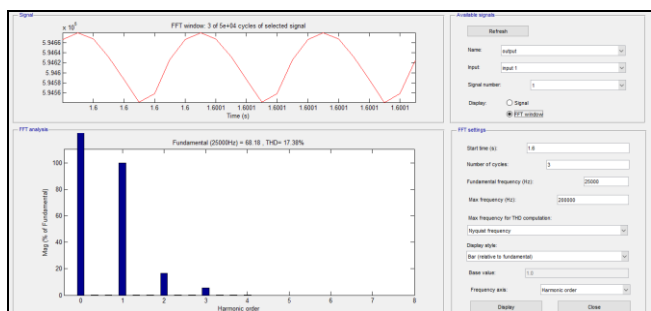

Figure 17: Total harmonic distortion for output voltage

Figure 17 shows the total harmonic distortion relative to fundamental frequency of 25 kHz. The THD is 17.38%. The figure shows the magnitude of the fundamental and the harmonic order. It shows that there is a bit increasing in THD from the first stage rectification to the last stage. A small harmonic distortion produces by the boost circuit.

A circuit of power factor is designed and attached to the three-phase V-I measurement at the AC source. A power factor is calculated at range of 0 to 1. A unity power factor is important as it give high efficiency of the system. The designed circuit is according to the power factor formula which is the apparent power divided by real power as shown in figure 18. The measured power factor for this simulation work is 0.98, approximately unity pf.

Power factor, $pf = \dfrac{real\,power}{apparent\,power} = \dfrac{P}{S}$ (7)

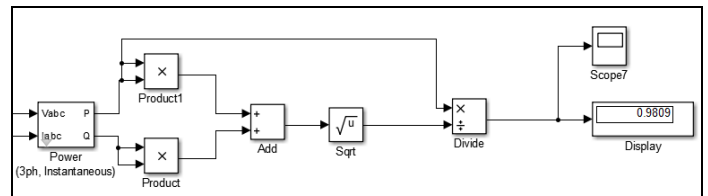$apparent\,power, S = \sqrt{P^2 + Q^2}$, where; Q = reactive power

Figure 18: Power factor circuit

Conclusions

This paper presents the simulation of power converter form AC to DC and DC to DC for high voltage DC transmission. A three-phase 6-pulse diode rectifier with an LC filter and boost converter has been implemented and simulated. A 600 kV DC source is obtained with lower harmonics and high power factor. Simulated results show that the total harmonic distortion is less than 20% with power factor up to 0.98 approximated to unity. Therefore, this system safe to feed the transmission cable as can protect the electrical equipment. However, the limitation of the time constant for the output voltage to be linear is around 0.1 to 0.6 sec. The suggestion of future work is by using 12-pulse and 18-pulse of rectifier and other types of DC converter such as fly-back or Cockcroft Walton voltage multiplier.

References

1. Nader Barsoum: "Implementation of a Higher Quality DC Power Converter", Journal of Electromagnetic Analysis and Application (JEMAA), China, Jan. 2010, Vol.2, No.2, ISSN: 1942-0749, Online publication
2. J.L. Jordão, S.F. Pinto, J.F. Silva. (2015). Modular Multilevel Converter for Bidirectional HVDC Transmission. Dep. of Electrical and Computer Engineering, UMS Letter.
3. Bernt Bergdahl, Rebati Dass. (2018.). AC-DC Harmonic Filters for Three Gorges-Changzhou 500kV HVDC Project. ABB Power Systems, ABB Limited.
4. Gbadega, Akshay. (2018). Comparative study of Harmonics Reduction and Power Factor enhancement of Six and twelve-pulses HVDC system using passive and shunt APFs Harmonic Filters. 1-10.
5. Bernt Bergdahl, Rebati Dass. (2019). AC-DC Harmonic Filters for Three Gorges-Changzhou 500 kV hvdc Project.
6. Arif, Madiha, Jawad, Abdul. (2016). THD Analysis of Reduced Switch Five Level Inverter using Multicarrier PWM SChemes. Internationa conference on Frontiers of Information Technology, 1-5.
7. Ruchi, Sanjeev. (2014). Harmonic Mitigation in Voltage Source Converters based HVDC system Using 12-pulse AC-DC Converters. Annual IEEE India Conference, 1-6.
8. Texas. (2016). LC filter design. 1-41.