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Computational Complexity of Algorithms for Optimization of Multi-Hybrid Renewable Energy Systems

Famous O. Igbinovia, *Member, IEEE*, and Jiri Krupka

***Abstract*—A well designed algorithm helps to determine the optimum size of power generation system. And for Multi-Hybrid Renewable Energy Systems (MHRESs), comprising of two alternative energy systems working together, such as PV array, Wind turbine, and Hydro generation capacity for back-up and grid integrated MHRES of desired load, a thoroughly designed algorithm will nevertheless assist in the optimal sizing of such a MHRES. In this paper, MHRES was discussed and computational complexity of algorithms was briefly analyzed. These computational complexities are including of: Complexity of converting among Context Free Grammars (CFGs) and Pushdown Automata (PDAs); Running time of conversion to Chomsky Normal Form (CNF); Testing emptiness of Context Free Languages (CFLs); Testing membership in a Context Free Language (CFL); and Complexity of Primality Testing. This was done to understand the ingenious idea behind computational complexity of algorithm. Thereby giving an understanding on how fast a program for optimizing MHRES will be when it performs computations and how a MHRES algorithm will behave as the input grows larger.**

***Index Terms*—Computational complexity of algorithm, Hybrid energy system, Hybrid renewable energy system (HRES), Optimization of HRES, Renewable energy system.**

I. INTRODUCTION

ELECTRIC power systems are comprised of components that produce electrical energy and transmit this energy to consumers. A modern electric power system has mainly six main components, these are: power plants which generate electric power; transformers which raise or lower the voltages as needed; transmission lines to carry power; substations at which the voltage is stepped down for carrying power over the distribution lines; distribution lines; and distribution transformers which lower the voltage to the level needed for the consumer equipment. The production and transmission of electricity is relatively efficient and inexpensive, although unlike other forms of energy, electricity is not easily stored, and thus, must be produced based on demand [1]. In the future, it is expected that electrical energy production area and network grid structure will change. More dispersed renewable generation units, such as Photovoltaic (PV) systems, biomass systems and small Wind Generators (WGs) will be connected to the grid at the distribution level where also new loads will give interactions to the transport, thermal and gas sectors via electrical vehicles, heat pumps, electrolysers etc. Further, there is an increasing focus on the connection of large offshore wind farms, reinforcement of the transmission grid and on more High Voltage Direct Current (HVDC) connections at the transmission level [2] – [3]. Renewable based electricity generation are well-thoroughly considered to be alternate source of green power generation which can mitigate power demand issues [4]. This may offer potential financial, environmental and technical benefits, but it also presents a great number of challenges and uncertainties [2]. Depending on the connection of power systems to the main grid, small power systems can be broadly classified into grid-tied system and off-grid power systems. Almost all the small power systems that are designed and optimized to meet the power demand of remote places are off-grid power systems. An off-grid system does not have a connection to the main electricity grid. A grid connected system is connected to a larger independent grid typically the public electricity gird and feeds energy directly into the grid. The feeding of electricity into the grid requires the transformation of Direct Current (DC) into Alternating Current (AC) by a synchronizing grid-tie inverter [5]. Fig. 1 shows each type of power systems in detail.

A hybrid power system is a developing power generation technique which comprises a combination of different energy systems, mostly renewables for optimal power output.

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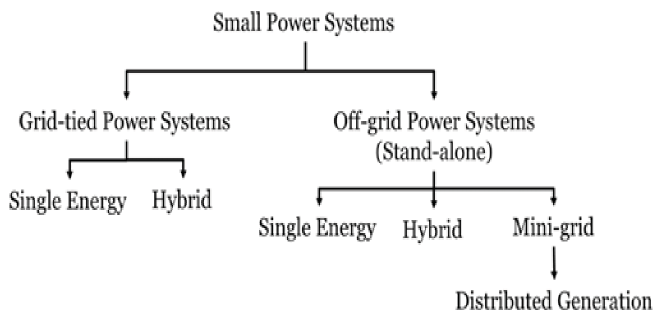

Fig. 1. Classes of power systems based on grid connection [5].

A combination of different but complementary energy generation systems based on renewable energies or mixed (that is Renewable Energy Source (RES) with a backup of Liquefied Petroleum Gas (LPG)/diesel/gasoline generation set), is known as a hybrid power system [6], [7]. Hybrid power systems are designed for the generation and use of electrical power. They are independent of a large, centralized electricity grid and incorporate more than one type of power source. They may range in size from relatively large island grids of many megawatts to individual household power supplies on the order of one kilowatt [8]. Hybrid power systems are designed for the generation of electrical power using several power generation devices such as wind turbine, PV, micro hydro and/or other conventional generators using fossil fuels. Such systems can range from small system capable of providing power for a single home to large system which can power a village or an island. Hybrid power systems are thought to provide power to many remote communities especially in the developing world where national grid is economically and technically not viable [5]. The system can be a combination of solar source with wind turbine and battery banks, the benefit of such system is its reliability and complementarity in producing electricity. It is the best solution for electrifying remote and isolated places. These independent energy systems are becoming more popular for some reasons, which are increasing fossil fuel costs and decreasing prices of turbines and PV panels [9] – [12]. Hybrid systems enable the incorporation of renewable energy sources and the transferals dependency on fossil fuels, while sustaining the balance between supply and demand of electricity. The significant characteristic of hybrid power system includes, system reliability and operational efficiency. The hybrid power system helps to overcome the limitations in wind and photovoltaic resources since their performance characteristics depends upon the unfavorable changes in environmental conditions. It is probable to endorse that hybrid stand-alone electricity generation systems are usually more reliable and less costly than systems that depend on a single source of energy. On the other hand, environmental condition can make one type of RES more profitable than another. For instance, PV systems are ideal for locations having more solar illumination levels and wind power systems are ideal for locations having better wind flow conditions. A Multi Hybrid Renewable Energy System consists of two alternative renewable energy systems working together. [4], [13] - [16].

An algorithm is a list of rules to follow to solve a problem. It is a set of guidelines that describe how to perform a task and can be said to be a detailed set of instructions/rules which enable a program to perform a specific action. An algorithm is any structured method for solving a problem. It can be an equation, or several steps, or a combination of both. A set of rules is usually followed in problem solving operations, particularly when considering the computer machine. Code is used to tell a computer what to do. Before a code is written an algorithm is needed. Algorithms need to have their steps in the right order. When an algorithm is written the order of the instructions is very important [17] - [19].

Computational complexity of an algorithm is the study of how long a program will take to run, depending on the size of its input and how long the loops made inside the code is. Specifically, the complexity of an algorithm is a measure of how long it takes to complete. Computational complexity of an algorithm is a measure of the amount of time and/or space required by an algorithm for an input of a given size (n). Thus, computational complexity is not concerned with how long it took an algorithm to run using X amount of data. Rather, it is concerned with the relationship in runtime when using X amount of data, 2X amounts of data, 10X amounts of data, and so on. Computational complexity is usually referred to as execution time, it can also be applied to other resource usage like memory allocation. In all cases, complexity is concerned with the relationship between the rate of increase in resource consumption and the rate of increase of the size of the data set being worked on. [19] - [20]. Algorithm computational complexity is a theoretical metric that is applied to algorithms to measure them. It is a basic and important concept for all programmers [21].

Optimization is a method of finding the optimum solution, that is finding the maximum or minimum of a given objective, subjected to various constraints [22]. Optimization in power system is a broad set of interrelated decisions on obtaining, operating, and maintaining physical and human resources for electricity generation, transmission, and distribution that minimize the total cost of providing electricity to all classes of consumers, subject to engineering, market, and regulatory constraints [23]. Designing a hybrid system involves many variables, therefore classical methods of optimization do not give optimal results, so also is multi hybrid system, for this reason the evolutionary methods must be used. Optimization methods can be used to achieve a good compromise between electricity loads and power system costs. Recently different methods have been applied to optimize the size of hybrid renewable energy systems such as linear programming, and iterative technique to minimize system cost. Techniques like Genetic algorithm has been used for sizing power systems to guarantee its reliability; therefore, it is necessary to choose the best combination of components and their numbers to achieve best result [12], [24] – [27].

This paper talk about multi hybrid renewable energy systems. It analyses computational complexity of algorithms. The computational complexities analyzed are: Complexity of converting among Context Free Grammars (CFGs) and Pushdown Automata (PDAs); Running time of conversion to Chomsky Normal Form (CNF); Testing emptiness of Context Free Languages (CFLs); Testing membership in a Context Free Language (CFL); and Complexity of primality testing. It is expected that this study will help in knowing how fast a program for optimizing MHRES will be when it performs computations and how a MHRES algorithm will behave as the input grows larger.

II. Motivation

The motivation for this work originates from the fact that algorithms are programs that perform computational task and computers are often used to do such work as networking tasks or user input and output. Hence, computational complexity analysis will help to measure how fast a program is when it performs computations. Computational complexity analysis is also a tool that can help to explain how an algorithm behaves as the input grows larger. It can equally help to develop an algorithm characterized by high performance and lower complexity that will allow effective modelling and design of an optimized MHRES scheme.

III. Multi Hybrid Renewable Power System

A Hybrid Renewable Energy System (HRES) is a power network which comprises of a combination of different renewable energy generators for the optimal output of an electric-power system. The first village hybrid power systems consisting of PV and diesel generator was installed on December 16, 1978 in Papago Indian Village, Schuchuli, Arizona, USA. The power produced by the system was used for providing electricity for community refrigerator, washing machine, sewing machine, water pumps and lights until an electric grid was extended to the village in 1983 [28], a simple renewable hybrid system is shown in Fig. 2.

In recent years, more than one renewable form of energy is being used in Hybrid Renewable Energy System. Micro hydro power (MHP), PV and small wind power sources with or without energy storage devices are widely used for providing electric-power to consumers in remote areas. Different alternative energy resources have different production characteristics, water in river changes flow according to seasons, solar irradiation is greater in summer than winter season and higher in day time and non at night, wind speed is greater in summer time. Thus, they are usually used in hybrid renewable system configurations [5].

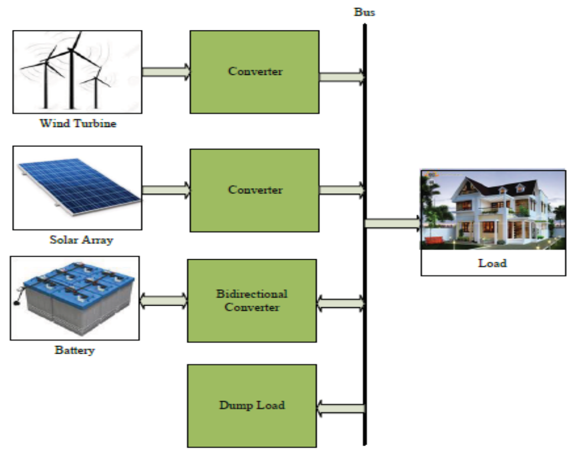

Fig. 2. Hybrid renewable power system [29].

The merits of HRESs are as follow: Two or more renewable energy sources can be integrated in one system, based on the local renewable energy potential. No any form of emission is produced from all renewable energy hybrid system like PV, Wind and Hydro integrated systems. Modular PV and wind systems are easy to install and, in most case, needs no design for domestic usage. Smaller hybrid systems are cheaper than larger and complex systems like nuclear power schemes. Small hybrid system is best suited for off-grid electrification. Fuel for HRES is abundant, free and inexhaustible hence electric energy produced by these systems is independent of fuel price. Standalone commercial PV or wind systems do not produce power round the clock and throughout the year, therefore, combining PV and wind has the benefit of reduced battery bank capacity and diesel requirements (in case it has conventional generator as back up) among other benefits. Nevertheless, for better performance of hybrid PV-Wind system, good potential of solar irradiation as well as wind energy is a must at the chosen site of installation. Environmental factors, PV capacity (the number of PV panel), wind generator capacity (the size of wind generator), storage device capacity (the number of battery), generation site (distance between power plant and consumer), and so on, play an important role in operation, maintenance and cost of a hybrid PV/wind - diesel system [5]. The block diagram of a typical hybrid PV/wind system with battery storage is illustrated in Fig. 3.

Evaluation of the general performance of a stand-alone hybrid PV/wind system can be done using computer-modeling approach. In the design of the optimal combination and unit sizing for wind-PV and tied hybrid system, some school of thought posit that optimal solution can be obtained if PV contributed 75% of the energy requirements, but this depends on the renewable energy source available in such location [30] – [35].

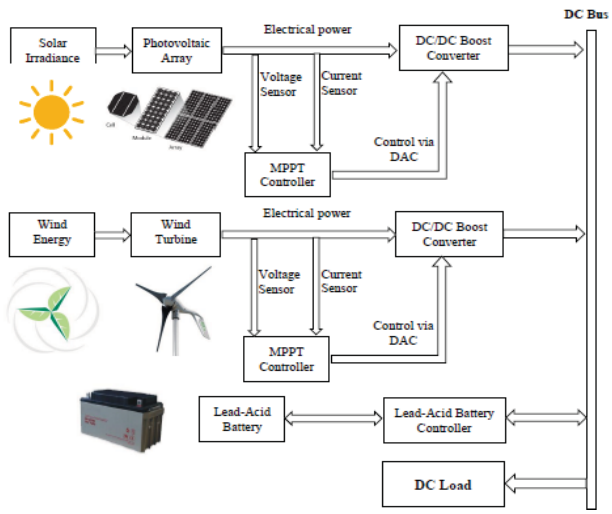

Fig. 3. Block diagram of a hybrid PV/wind system with battery storage [30].

Hybrid energy system consisting of PV, and wind, can be tied with diesel generator and battery backup. The study of the impact of variation of PV array area, number of wind generator and battery storage capacity of HRES can be a proposed decision support technique for policy makers in influencing the factors in the design of grid linked hybrid PV-wind renewable power systems, these factors can be political, social, technical, and economical [31] – [35].

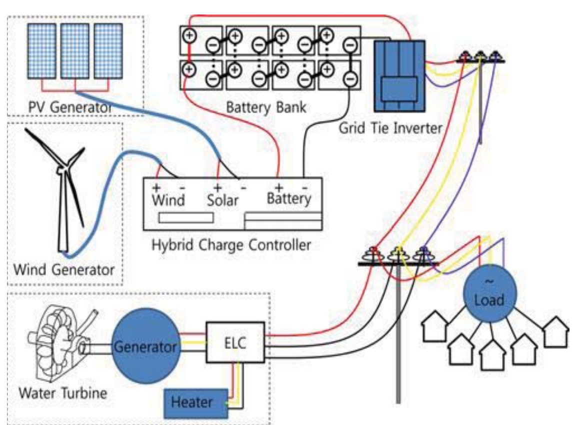

Fig. 4. Schematic diagram of a typical hybrid micro hydro power (MHP)-PV-Wind system [5].

The block diagram of a stand-alone hybrid MHP-PV-WG is shown in Fig. 4. In the figure, a hybrid charge controller is used to connect two power sources (PV-WG). Depending on the load the excess power is used to charge the battery bank. The battery bank is used to store the surplus energy and to supply power to the load in case of insufficient power generation from the hybrid renewable power system. The inverter is required to change DC voltage to AC voltage to meet consumer load demand. The outputs of all battery chargers, the battery bank and the DC/AC converter input terminals are connected in parallel. The instantaneous change in solar irradiation and wind speed characteristics highly influences power production thus careful designed hybrid renewable electric-power system can reliably supply electricity to consumers under varying atmospheric condition. In the same way a carefully designed system should be made to keep the system cost low [5].

A multi hybrid system consists of two alternative energy systems working together. Hence, a multi hybrid renewable energy system consists of two alternative renewable energy systems working together. An island system helps to secures backup power to the "essential" appliances. A Grid-connected system feeds power to both the essential and non-essential appliances. The topology of a MHRES allows it to function as a full island system under grid failure, ensuring an unlimited power supply to all the essentials. The merits of a MHRES are as follows: Expandable in both the island and grid capacities; Reliable supply for essential appliances; Surplus power is fed back into the grid and not dissipated as in island systems; Batteries will not be cycling if grid power is available; Essential appliances can be selected and added; Standby batteries in this application can achieve similar life to cyclic batteries in a cyclic application Battery backup is only for essential equipment resulting in a reduced battery bank. If grid power is available, multi hybrid and MHRESs are not needed [16].

IV. COMPUTATIONAL COMPLEXITY OF ALGORITHMS FOR OPTIMIZING MULTI-HYBRID RENEWABLE ENERGY SYSTEMS

Computational complexity is considered as the study of the efficiency of algorithms. Therefore, computational complexity of algorithms for optimizing HRESs is the study of the efficiency of algorithms for optimizing HRESs. Complexity complements computability by separating problems that can be solved in practice from those that can be solved only in principle. In studying complexity, it is necessary to ignore many details, such as the particulars of hardware, software, data structures, and implementation, and look at common, fundamental issues. For this reason, the orders-of-magnitude expressions is very important. Efficiency is measured by resource requirements, such as time and space, that is time-complexity and space-complexity. Time-complexity is a rough measure of the time taken by a computation. While space Complexity is the total space taken by an algorithm with respect to the input size, it includes both Auxiliary space (that is the extra space or temporary space used by an algorithm) and space used by input. Time-complexity is a little more accessible and, at the same time, more useful [36] - [38]. Problems of high complexity can be practically viable if the complexity is caused by a parameter, which tends to be small in the applications [39]. Some computational complexity of algorithms useful for optimizing HRESs are as follows:

A. Complexity of Converting Among Context Free Grammars (CFGs) and Pushdown Automata (PDAs)

A context free grammar (CFG) is a mathematical structure that compactly describes the set of valid strings that can occur in a language [40]. It is a class of formal grammar, containing productions for the description of the set of strings in a given formal language [41]. A CFG is a set of recursive rewriting rules (or productions) employed to generate patterns of strings. CFGs can be used to describe the syntax of the input of a system under test. And test cases can be generated conforming to the grammar of context-free grammar [42]. Context-Free Grammar is a Type-2 Chomsky grammar commonly used to represent the syntax of programming languages and files but are equally an effective means of compressing the essential information from data streams, a Chomsky grammar hierarchy is shown in Fig. 5. [43]. Chomsky hierarchy of languages arranges language classification by the level of computational power necessary to identify them [44]. From the lowest to highest computational power, the hierarchy is made up of the regular languages (Type-3), the context-free languages (Type-2), the context-sensitive languages (Type-1), and the unrestricted languages (Type-0). Context free languages can be referred to as unambiguous (that is deterministic) and ambiguous (that is nondeterministic). Recognizers for the four classes of the hierarchy separately requires finite-state machines, push-down automata, linear-bounded automata, and Turing machines [45].

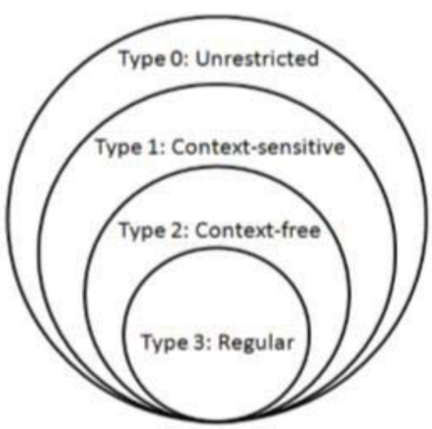

Fig. 5. Chomsky grammar hierarchy [43].

Context-free grammars are PDA with one state where each transition pops exactly one symbol off the stack [46]. Context-free language defined over a one-letter alphabet is regular. This implies that unary context-free grammars and unary pushdown automata can be transformed into equivalent finite automata [47]. Considering the complexity of converting from one representation to another. The running time of the conversion is a component of the cost of the decision algorithm whenever the language is given in a form other than the one for which the algorithm is designed. For instance, if n be the length of the entire representation of a Pushdown Automaton (PDA) or CFG. Using this parameter as the representation of the size of the grammar or automaton is coarse, in the sense that some algorithms have a running time that could be described more precisely in terms of more specific parameters such as the number of variables of a grammar or the sum of the lengths of the stack strings that appear in the transition function of a PDA. Regardless of how, the total length measure is sufficient to distinguish the most important issues, such as; is an algorithm linear in length (that is does it take little more time than it takes to read its input), is it exponential in length (that is can the conversion be perform only for rather small examples), or is it some nonlinear polynomial (that is can the algorithm be run even for large examples, it is of note that the time is often quite significant) [48]. PDAs provide a more suitable framework to achieve exact decoding for larger synchronous context-free grammars and smaller language models [49].

There are several conversions that are linear in the size of the input. Since they take linear time the representation that they produce as output is not only produced quickly, but it is of size comparable to the input size. These conversions are: Converting a CFG to a PDA; Converting a PDA that accepts by final state to a PDA that accepts by empty stack; and Converting a PDA that accepts by empty stack to a PDA that accepts by final state [48]. Boundedness is a structural limitation on context-free languages which reduces non-recursive tradeoffs to recursive trade-offs. Context-free grammars and pushdown automata for bounded languages are much more manageable from a practical point of view than in the general case [50]. Pushdown automata conversion to a context-free grammar has a linear time and space complexity, the running time of the conversion from a PDA to a grammar is much more complex [48], [51]. The running time of the conversion can be exponential if there is a transition of the PDA that puts many symbols on the stack [48].

B. Running Time of Conversion to Chomsky Normal Form (CNF)

A CFG is said to be in Chomsky Normal Form of Grammar only if the right-hand side of a production must have two non-terminal symbols or single terminal symbol [52]. A given grammar can be transformed into a cleaner form, that is the Chomsky Normal Form [53]. Chomsky Normal Form (CNF) is a simple and useful form of a CFG, any context free language may be generated by a context free grammar in Chomsky Normal Form, Chomsky Normal Form is useful to interpret a grammar as a parse tree [54]. As decision algorithms may depend on first putting a CFG into Chomsky Normal Form (CNF), hence it is important to look at the running time of the various algorithms that is used to convert an arbitrary grammar to a CNF grammar. Most of the steps preserve up to a constant factor the length of the grammars description that is starting with a grammar of length n producing another grammar of length O(n). The merit of this is that: Using the proper algorithm, detecting the reachable and generating symbols of a grammar can be done in O(n) time, eliminating the resulting useless symbols takes O(n) time and does not increase the size of the grammar; Constructing the unit pairs and eliminating unit productions, takes O(n) time and the resulting grammar has length O(n); The replacement of terminals by variables in production bodies (that is Chomsky Normal Form) takes O(n) time and results in a grammar whose length is O(n); The breaking of production bodies of length three or more into bodies of length two also takes O(n) time and results in a grammar of length O(n) [48], [55].

The demerit of this construction is in eliminating ϵ-productions. If there is a production body of length k, it could be constructed from that one production 2k - 1 productions for the new grammar. Since k could be proportional to n this part of the construction could take O(2n) time and result in a grammar whose length is O(2n). To avoid this exponential blowup, it is needed only to bound the length of production bodies. Thus, as a preliminary step before eliminating ϵ-productions, the breaking of all long production bodies into a sequence of productions with bodies of length two. This step takes O(n) time and grows the grammar only linearly. Eliminating ϵ-productions will work on bodies of length at most two in such a way that the running time is O(n) and the resulting grammar has length O(n). With this modification to the overall CNF construction the only step that is not linear is the elimination of unit productions, that is step O(n^2) [48], [55].

C. Testing Emptiness of Context Free Languages (CFLs)

Emptiness test includes generating and reachability test. It can detect variables that generate no terminal string. Considering the generating test of a CFL: Given a grammar G for the language L and deciding whether the start symbol S of G is generating, that is whether S derives at least one string. L is empty if and only if S is not generating. Now considering in detail how much time it takes to find all the generating symbols of a grammar G. Suppose the length of G is n. Then there could be on the order of n variables and each pass of the inductive discovery of generating variables taking O(n) time to examine all the productions of G. If only one new generating variable is discovered on each pass, then there could be O(n) passes. Thus, a naive implementation of the generating symbols test is O(n^2). Regardless of how, a more careful algorithm can set up data structure in advance to make the discovery of generating symbols take O(n) time only [48].

D. Testing Membership in a Context Free Language (CFL)

A string can be run through a machine and see where it goes since PDAs are non-deterministic, all possible paths are put into consideration [56]. In deciding membership of a string ω in a CFL L, it takes a time that is exponential in ω. Assuming a grammar or PDA for the language L is given and its size is treated as a constant independent of ω. It can be started for instance by converting whatever representation of L given into a CNF grammar for L. As the parse trees of a Chomsky Normal Form grammar are binary trees, if ω is of length n then there will be exactly 2n-1 nodes labeled by variables in the tree. The number of possible trees and node labeling is thus only exponential in n. A much more efficient technique is dynamic programming, that is table-filling algorithm or tabulation, when computing with this method, the running time of the grammar itself is considered fixed and its size contributes only a constant factor to the running time, which is measured in terms of the length of the string ω whose membership in L is being tested [48], [57].

E. Complexity of Primality Testing

A primality test is simply an algorithm that tests either deterministically or probabilistically, that is whether a given input number is prime [58]. Deterministic primality tests have zero rate of failure, but very high running times. Whereas, probabilistic tests have low running times but higher rates of failure [59]. A general primality test does not provide a prime factorization of a number not found to be prime, but simply labels it as composite [58]. Interest in the problem of determining the exact complexity of primality testing has persisted from the establishment of computational complexity theory to present day, there are polynomial size circuits which test primality [60]. Improving the time complexity of primality testing algorithm remains a major problem [61].

Primality testing are essential ingredients in computer-security systems. There are several techniques that enhance computer security, relying on the assumption that it is hard to factor numbers, that is, given a composite number, to find its prime factors. These schemes, based on what is called RSA (Rivest–Shamir–Adleman) codes, uses integers of, say, 128 bits that are the product of two primes, each of about 64 bits. This is important in Public-Key Cryptography and Public-Key Signatures. Both scenarios work and is secure, in the sense that it really does take exponential time to factor the product of two large primes. The construction of public keys requires being able to find large primes quickly. While the security depends on there being no polynomial way to factor in general [48], [62]. There are some primality tests which conclusively determine whether a number is prime or composite and are therefore deterministic, while some despite correctly classifying all prime numbers, may allow some composites to filter through, incorrectly labelling them as primes or probably primes, and this makes these tests probabilistic [58]. Although there had been many probabilistic algorithms for primality testing, there was no deterministic polynomial time algorithm until Agrawal, Kayal and Saxena came with an algorithm, popularly known as the AKS algorithm, which could test whether a given number is prime or composite in polynomial time [63]. AKS test has indeed provided an unconditional, general, deterministic and polynomial-time algorithm for primality-testing. However, despite being polynomial in complexity and deterministic, other probabilistic tests have a lower time-complexity and can provide larger primes needed for, say, cryptography with high enough accuracy. There are usually four criteria which is look for in an efficient primality-testing algorithm: it must be general, unconditional, deterministic and polynomial in complexity [58].

In cryptography, for example, there is often need for the generation of large primes and one technique for this is to pick a random number of requisite size and determine if it's prime. The larger the number, the greater will be the time required to test this and this is what prompted the search for efficient primality tests that are polynomial in complexity. It is of note that the desired complexity is logarithmic in the number itself and hence polynomial in its bit-size as a number n requires O (log n) bits for its binary representation [58].

V. Conclusion

Computational complexity of algorithm for optimizing multi hybrid renewable energy systems is the study of how long a program will take to run in optimizing MHRES designed scheme, depending on the size of its input and how long the loops is made inside the code. It is thought that MHRES will be instrumental for providing electricity to majority of people who are deprived of electricity mostly in developing countries. Instead of single generation system like PV or Wind, MHRES can harvest energy even when potential of one is minimal, which thereby increases power reliability. In this paper, multi hybrid renewable energy systems and the computational complexity of algorithm for multi hybrid renewable power systems have been discussed. The authors have been able to meet the modest target of basically studying and having a good understanding of the computational complexity of algorithms. But there is need towards using this knowledge in making algorithms more practical in applying it to Multi Hybrid Renewable Energy Systems. Future work is needed on the development of an in-depth optimized MHRES grid tied model and the choice/implementation of an appropriate algorithm using software to arrive at practical solution. And putting into consideration the fastness and behavior of the algorithm as the input grows large.

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