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Availability of Wind Turbine Converters With Extreme Modularity

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***Abstract*—Modularity is promising from a view to increasing turbine availability through fault tolerant operation as well as reduced downtimes, especially for offshore wind turbines. This paper focuses on a quantitative analysis of large scale (or extreme) modularity in power electronic converters of wind turbine generator systems. It uses mathematical models to investigate the effect of the choice of module number on the availability of a converter. It further analyses the availability in conditions where increased levels of modularity lead to a reduction of failure rates in the system. The paper extends this analysis by quantifying the benefits for a 10-MW case study turbine. Finally, it concludes that extreme modularity holds merit only when it is accompanied by a reduction in failure rates.**

***Index Terms*—Availability, modularity, wind turbine, power electronic converter, Markov modeling.**

I. Introduction

POWER electronic converters have been shown to be a major contributor to the failure rates of wind turbine drivetrains [1]–[7]. This makes addressing their failures and improving their availability an important route towards reducing cost of energy. One method of doing this is though the addition of modularity in the converter system [8]. Modularisation is a design approach that decomposes a system into a number of 'modules' or components. The motivations behind the use of this concept have been diverse: from increasing manufacturability in machines, and standardisation of parts for the supply chain, to improving part load efficiency and system reliability. For wind turbines, this concept is attractive from the perspective of improving the availability of the turbine system predominantly in two ways. First, the introduction of fault tolerance, where the faulted module is bypassed and the remaining system continues operation with the same or a lower rating. Second, the increased maintainability of such a system, by making failed modules easier and cheaper to replace.

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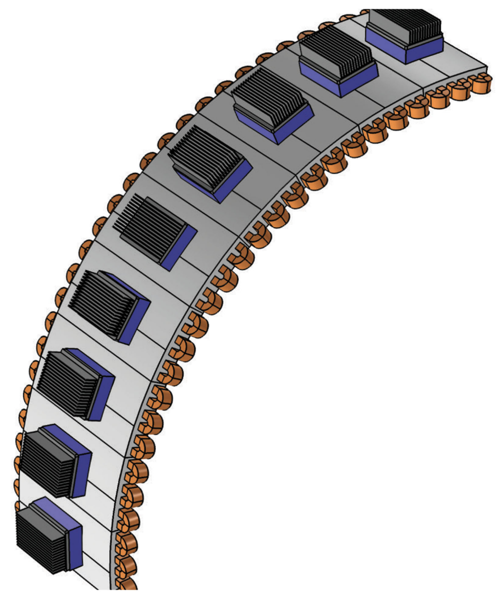

Fig. 1. Extreme or large scale modularity with each set of three-phase winding sets being fed by a modular power electronic converter. Such systems use a large number of converter modules to process the net power produced by the wind turbine.

In [8], the authors describe modularity at two levels for a wind turbine generator system-functional and physical modularity. While functional modularity is a way to introduce fault tolerance to a system, the addition of physical modularity improves the maintainability of a system. Modularity has been explored in literature, multiple modules that form pairs of interchangeable converter modules is one example [9], and the system with six parallel connected converters for a 4.5 MW commercial wind turbine is another [10]. Further, the integrated modular motor drive concept for traction [11] and aerospace applications [12] utilise modularity to allow for fault tolerant operation. However, extreme modularity has not been implemented in wind turbine generators yet.

This paper takes a first step towards extremely modular generators by analysing the effect of functional and physical modularity on the availability of the converter in a wind turbine. Furthermore, it focusses on extreme modularity-i.e., designs where the number of modules is much larger than what is used at present (in the industry). Fig. 1 shows an example of an extremely modular system, where each set of three phase winding segments are powered by a modular power electronic converter.

The paper investigates the effect of modularity on the converter availability using Markov state space models [13] to quantify these effects. The use of Markov modelling is one approach towards system level reliability modelling with the advantage that it is an effective tool for fault tolerant systems [14]. Markov models have been used to investigate maintenance planning in [15], optimum maintenance policies in [16], operational comparison of technologies in [17], and reliability of potential wind farms in [18]. In power electronics, this modelling tool has been used by *Zhang et al.* to investigate the reliability of modular converters for wind turbines [19] based on a patented design [9]. Furthermore, *Najmi et al.* use Markov models to model the reliability of capacitor banks for modular multilevel converters [20], and *McDonald et al.* investigate parallel wind turbine powertrains in [21]. Other work has used variations of these methods to investigate redundancy in converters; such as that of HVDC MMC modules in [22], and parallel-inverter systems in [23].

The contribution of this paper is that it investigates extreme modularity along with the effect of additional factors that come into play with such extreme modularity. The aim of this paper is to give a detailed overview of the effect of extreme modularity on the performance of a wind turbine generator system which could serve as a reference for future wind turbine designs that use large scale modularity in the generator system with the aim of maximising the availability of the turbine.

The paper is organised starting with Section II that gives some background on failures in wind turbine converters, and Section III that defines the starting assumptions and performance indices. Section IV analyses the modular system in a condition of continuous repair while Section V considers the condition of periodic repair. Section VI considers the availability of modular systems when the failure rates reduce with the increased level of modularity. The case study in Section VII quantifies the analyses of the previous sections for an example 10 MW turbine. Finally, conclusions from this study are detailed in Section VIII.

II. Failures in Converters

Studies demonstrate that the converter is a major sources of failures in a wind turbine [1]–[7]. Spinato *et al.* studied failure data from three different studies (the WindStats data for Germany and Denmark, and the LandwirtschaftKammer data for Germany) and found the converter failure rate to be approximately 0.20 failures turbine^{-1}year^{-1}. Two more recent studies that have focussed on failure rates in offshore wind turbines, Carroll *et al.* analysed the failures for a population of approximately 350 offshore wind turbines with nominal power between 24MW and found failure rates of 0.18 failures turbine^{-1}year^{-1}, while the SPARTA initiative in the UK that monitors approximately 1400 offshore wind turbines found a failure rate of 1.32 failures turbine^{-1}year^{-1} for the converter.

The difference in rates can be explained by the difference in drivetrain topologies. The SPARTA project uses data from UK offshore wind farms where the majority of turbines use full scale converters with either permanent magnet generators, or squirrel-cage induction generators (more than 80% of the installed capacity). The use of these topologies reduces the failure mechanisms (and hence failure rates) in the generator by avoiding the use of slip rings, but uses full scale power converters which see a higher failure rate. On the other hand, the study by Carroll *et al.* have a large number of doubly fed induction machines fed by partially rated converters in the analysed population (based on slip ring issues being the major cause of generator failures) leading to a larger generator failure rate.

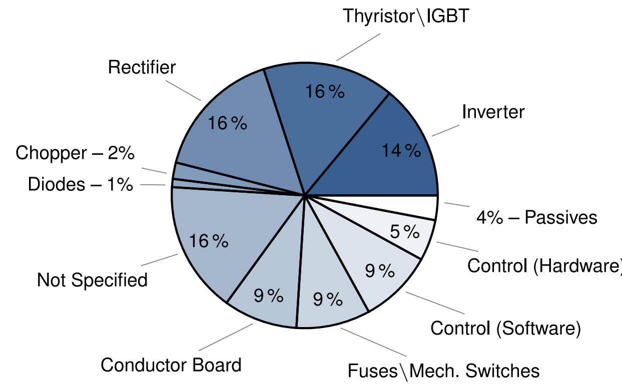

Fig. 2. Sub-component level failure distribution in power electronic converters. From [4].

There has been little published data on failures in wind turbines at a sub-component level. Lyding *et al.* [4] have studied failure rates of power electronic converters at a sub-component level with data from the WMEP database which is a monitoring programme that ran between 1989–2006. Fig. 2 shows the distribution of failures amongst converter sub-components based on this study.

This shows that the majority of failures involve the power semiconductors. An industry based survey by Bryant *et al.* gave similar results with maximum respondents selecting semiconductor power devices as the most fragile component in converters [24].

Another study by Carroll *et al.* analysed failures in drivetrains of 2222 onshore wind turbines between 1.5 MW to 2.5 MW. The wind turbine population consists of doubly fed induction generators (DFIG) with a partially rated converters and permanent magnet generators (PMG) with fully rated converters. The population of the DFIG configuration builds up to 1822 turbines over five years and the PMG population builds to 400 turbines over three years. Figs. 3 and 4 show the distribution of failures in converters from this study.

The study finds that the fully rated converter fails approximately 5.5 times as much as the partially rated converter. The higher failure rate is due to the higher losses that could cause cooling issues as well as greater stresses on the converter. In both these converters, the cooling system, the control modules, and the electrical connection issues are the main contributors. In this analysis, the gate driver and the IGBT are included in the electrical connection issues.

It is evident that the power converter has a high failure and modularity can be used to improve the availability of the system. This section has also shown that there is a large range of failure rates reported in literature and this paper uses the failure rate of 0.20 failures turbine^{-1}year^{-1} as the base case.

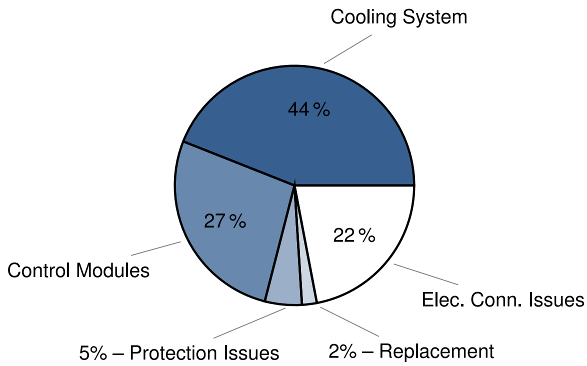

Fig. 3. Sub-component level failure distribution of fully rated converters. The data has been taken from [5].

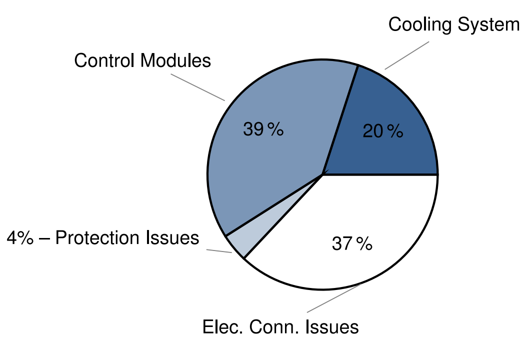

Fig. 4. Sub-component level failure distribution of partially rated converters. The data has been taken from [5].

III. Methodology

This paper investigates modularity in the power electronic converter of wind turbines. It starts by making a number of simplifying assumptions and then adding the required complexity in steps.

The converter system is assumed to be built-up of independent and identical parallel modules, such that the failure in one has no effect on the performance of the other. The failure rate is denoted by λ, which is identical for each module and is assumed to be constant (this may be thought of as the continuous failure region of the bathtub curve [25]). To begin with, it is also assumed that the failure rate is independent of the rating of the module. As an example, if λ is the failure rate with a single module, the failure rate with N modules will be $N \times$ λ. Furthermore, the rate of repair is denoted by μ.

Although Markov chains can be used to calculate probabilities of a system being in each state, it is easier to compare systems if they are defined by a single performance index. One such index used in this paper is the equivalent availability, given by

$$A_{eq} = \frac{\sum_{k=0}^{k=N} P_k p_k}{P}, \tag{1}$$

where N is the total number of modules, P_k is the power output of $State - k$ with a probability of p_k, and P is the rated power of the complete converter system. As an illustration, consider a case of a system with N identical modules with a combined power rating of P such that each module has a rating of $\frac{P}{N}$. The system has states from 0 to N, with $State - 0$ representing no failure (power production of P) and having a probability of occurrence of p_0 and $State - k$ representing failures in k modules (resulting in a power production of $\frac{N-k}{N}P$) with a probability of occurrence given by p_k. The effective availability of this system would be given by

$$A_{eq} = \left(P \cdot p_0 + \frac{N-1}{N} P \cdot p_1 + \cdots + \frac{N-k}{N} P \cdot p_k + \cdots \right.$$
$$\left. \cdots + \frac{1}{N} P \cdot p_{N-1} \right) / P, \tag{2}$$

or in a vectorised form

$$A_{eq} = \mathbf{P}^{\mathbf{T}} \cdot \mathbf{p}, \tag{3}$$

with the power fraction vector ($\mathbf{P}$) and the state probability vector ($\mathbf{p}$).

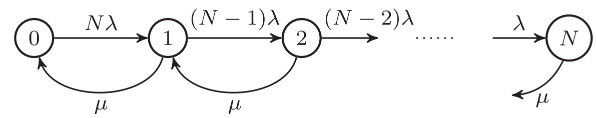

Fig. 5. Reduced state Markov chain with continuous repair.

IV. System With Continuous Repair

The simplest case is the case where the system is repaired once there is a failure with a repair rate of μ. The Markov state space model with reduced states is given in Fig. 5.

It can be shown that in this case the equivalent availability is independent of the number of modules [21], and is given by

$$A_{eq} = \frac{\mu}{\mu + \lambda}. \tag{4}$$

While there is no improvement in the equivalent availability of the converter system by adding modularity, the actual cost of repair would be higher because of an increased failure rate. This, however, is an impractical case as the basis of the introduction of modularity is to make the system fault tolerant and reduce the necessity of immediate repair.

V. System With Periodic Repair

One method to reduce the operating cost of a wind turbine is to eliminate unscheduled visits and only allow periodic scheduled maintenance. This would require the fault modules to go 'offline'while the healthy modules continue operation. All failed modules would be replaced in the periodic maintenance visit. Fig. 6(a) shows the expected availability of this system in time. The Markov state space representation of such a system is shown schematically in Fig. 6(b) with the system being reset to state 0 when $t = T_m$. Here the time taken for the maintenance is neglected. This is based on the assumption that the time for replacing the converters are much smaller than the maintenance period, due to which it is also assumed that the time for replacement is independent of the number of modules to be replaced. In this case too the effective availability remains independent of the number of modules.

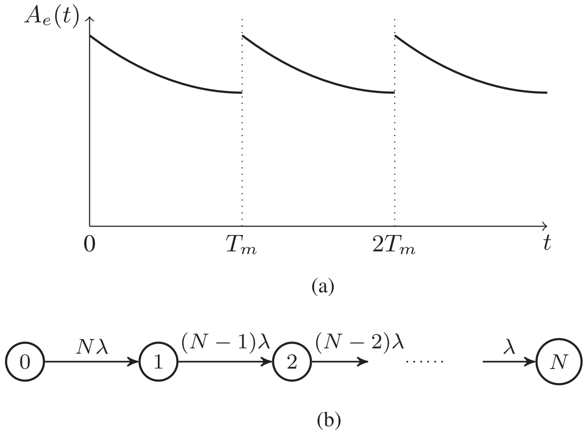

Fig. 6. System with periodic repair. (a) Plot of Availability with time. T_m represents the occurance of the periodic maintenance event. (b) Complete Markov chain.

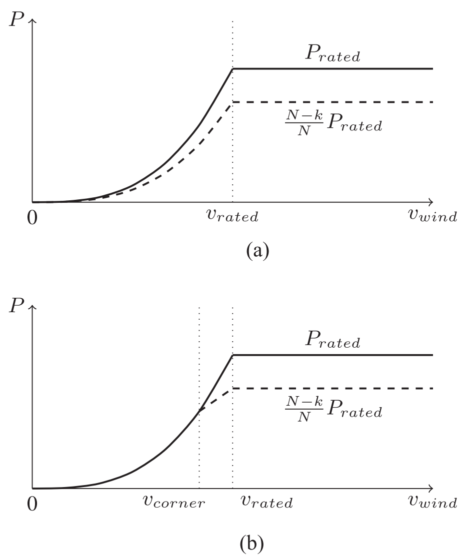

Fig. 7. System with periodic repair. (a) Power curve of a turbine with derating in case of module failure. The dashed line describes a turbine operating with failures in k modules with each module processing a power of $\frac{P}{N}$ resulting in a net turbine power of $\frac{N-k}{N}P$. (b) Power curve of a turbine considering partial loading. The dashed line describes a turbine operating with failures in k modules with each modules processing a power of $\frac{P}{N-k}$ till v_{corner} and $\frac{P_{\text{rated}}}{N}$ after v_{rated}.

The effective availability used to this point has only considered rated power conditions in its calculations and disregarded partial loading. Such a method is equivalent to derating the power curve in the event of module failure. However, wind turbines regularly operate at partial loads. This fact can be used to improve performance by allowing healthy modules to take a larger load in such partial loading conditions, while still remaining below the rated power of each module. The difference between these two approaches is highlighted using power curves in Fig. 7.

Fig. 7(b) shows that the operating region of the system at any $State - k$ (i.e. a condition where k modules have failed) has three regions:

- $v < v_{\text{corner}}$, where the net power output is equal to the unfaulted condition (this is achieved by allowing the healthy modules to take a larger share of the power while keeping this value lower than the rating of each module). This v_{corner} is defined as the wind speed where the module processes a current equal to its rated current. In this region, the turbine generates a torque equal to a condition with no faults. At $v = v_{\text{corner}}$, the turbine generates rated torque.
- $v_{\text{corner}} < v < v_{\text{rated}}$, where the torque is maintained at the rated value. The power increases linearly with the rotational speed.
- $v > v_{\text{rated}}$, where the torque and speed are maintained at the rated value. The power output in this region is given by $\frac{N-k}{N}P_{\text{rated}}$.

As $T \propto v_{\text{wind}}^2$, v_{corner} for $State - k$ can be given by,

$$v_{\text{corner}}(k) = \left(\frac{N-k}{N}\right)^{\frac{1}{2}} \cdot v_{\text{rated}} \tag{5}$$

Given that the wind velocity is characterised by a Weibull distribution with a shape factor a, and scale factor b, the power fraction vector can be updated using (6)–(7):

$$P(k) = \frac{\int_0^{v_c} P_g(v)f(v,a,b)\,dv + \int_{v_c}^{v_r} P_l(v)f(v,a,b)\,dv}{\int_0^{v_r} P_g(v)f(v,a,b)\,dv + \int_{v_r}^{\infty} P_r f(v,a,b)\,dv}$$
$$\cdots + \frac{\int_{v_r}^{\infty} \frac{N-k}{N} P_r f(v,a,b)\,dv}{\int_0^{v_r} P_g(v)f(v,a,b)\,dv + \int_{v_r}^{\infty} P_r f(v,a,b)\,dv},$$
$$P(k) = \frac{g(v_c, v_r, a, b, k)}{h(v_r, a, b)}, \tag{6}$$

with

$$g(v, v_r, a, b, k) = \left(\frac{b}{v_r}\right)^3 \left\{\frac{3}{a}\Gamma\left(\frac{3}{a}\right)\gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right)\right\}$$
$$+ \frac{N-k}{N}\frac{b}{v_r a}\Gamma\left(\frac{1}{a}\right)$$
$$\times \left\{\gamma\left(\left(\frac{v_r}{b}\right)^a, \frac{3}{a}\right) - \gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right)\right\},$$
$$h(v, a, b) = \left(\frac{b}{v_r}\right)^3 \left\{\frac{3}{a}\Gamma\left(\frac{3}{a}\right)\gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right)\right\}, \tag{7}$$

where $P_g(v)$ is the power curve of the generator system as a function of wind velocity, P_l is the linear power curve when $v_{\text{corner}} < v < v_{\text{rated}}$, $f(v,a,b)$ is the Weibull probability function with parameters a and b. $\Gamma(x)$ is the Gamma function and $\gamma(x,y)$ is the Incomplete Gamma function. The appendix explains the method used to obtain these results in more detail. No cut-out wind velocity is considered to simplify the expressions and the error due to this assumption is minimised by the use of the Weibull distribution which has an almost zero occurance for higher wind speeds.

This power fraction vector depends on the number of modules. The increase in the power fraction vector for an increase in the number of modules is estimated using $\frac{dP(k)}{dN}$. From (5)–(7),

TABLE I
MODELING PARAMETERS

Wind Speed Weibull Distribution		
Shape Parameter	a	2.1
Scale Parameter	b	11.29
Average Wind Speed	v_{avg}	10 m/s
Maintenance Parameters		
Failure Rate	λ	0.2 turbine^{-1}year^{-1}
Maintenance Period	T_m	1 year
Turbine Parameters		
Rated Wind Speed	v_{rated}	12 m/s

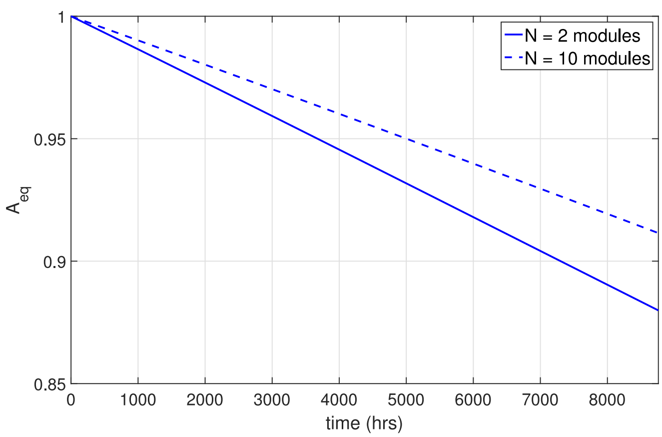

Fig. 8. Effective availability of the converter system with time over one maintenance period T_m. An increase in the number of modules leads to a greater effective availability.

this can be calculated to be

$$\frac{dP(k)}{dN} \propto \frac{d}{dN}\gamma\left(\left(\frac{v_c}{b}\right)^a, \frac{3}{a}\right),$$

$$\frac{dP(k)}{dN} \propto \frac{k}{N^2}\left\{\gamma\left(\left(\frac{v_c}{b}\right)^a, \frac{3}{a}\right) + \left(\frac{N-k}{N}\right)^{\frac{1}{3}} \cdots \right.$$
$$\left.\left(ln\left(\frac{3}{a}\right)\cdot\gamma\left(\left(\frac{v_c}{b}\right)^a, \frac{3}{a}\right) + \frac{3}{a}\cdot T\left(3, \left(\frac{v_c}{a}\right)^a, \frac{3}{a}\right)\right)\right\}, \tag{8}$$

where T is the Meijer G-function [26]. This expression advances two important conclusions; $P(k)$ is monotonically increasing, and the magnitude of this increase decreases with an increase in N. These conclusions can be extended to the equivalent availability, as the equivalent availability is a function of the power fraction and the state probability.

This model is now used to quantify the effect of the number of modules on the effective availability. The parameters used in the model are given in Table I.

The variation of the effective availability (A_e) in time is shown in Fig. 8 with two different number of modules. This shows that an increase in the number of modules (N) leads to an increase in effective availability.

If this effective availability is averaged over one maintenance period (T_m), the resulting 'averaged effective availability'

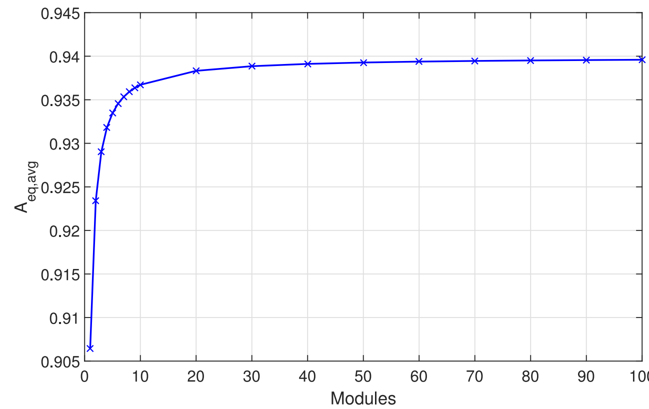

Fig. 9. Effect of the number of modules on the effective availability averaged over one maintenance period.

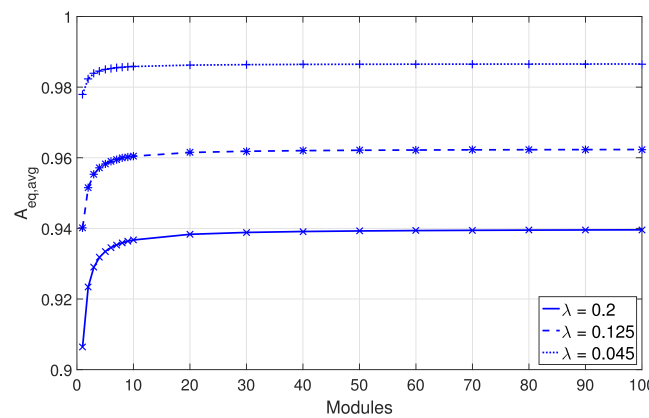

Fig. 10. Effect of the number of modules on the effective availability averaged over one maintenance period for different failure rates and $T_m = 1$ year.

($A_{e,avg}$) for different modular configurations can be compared. This is shown in Fig. 9. The figure shows that the expected improvement in the availability in the converter system is small for successive increments in the number of modules once $N > 20$ for the simplified model considered here, as can be expected based on (8).

A. *Effect of Failure Rates* (λ)

The failure rates of the converter modules impacts the availability of the turbine. There have been a number of studies that have studied the failure rates of wind turbine converters. *Spinato et al.* propose a failure rate of 0.2 turbine^{-1}year^{-1} based on the data from the LWK study in [3] while noting that the failure rates of converters from industrial experience are between 0.045–0.2 item^{-1}year^{-1} [3], [27]. Fig. 10 plots the effect of module numbers on effective availability for a few failure rates within this range.

It is logical that a higher failure rate results in a reduced effective availability. However, it is also seen here that the improvement due to the addition of modules is larger for larger failure rates. Therefore, modularity is more important when the higher failure rates are considered. This too is an intuitive result. Table II shows the improvements achieved when increasing the number of modules from 20 to 100 for different failure rates. It

TABLE II
IMPROVEMENT IN AVAILABILITY FOR EXTENSIVE MODULARITY (WRT λ)

T_m = 1 year			
Failure Rate λ	$A_{N=20}$	ΔA_{eq}	$A_{N=100}$-$A_{N=20}$
$\lambda = 0.045$	0.9862	0.0087	0.0004
$\lambda = 0.125$	0.9615	0.0222	0.0008
$\lambda = 0.200$	0.9383	0.0331	0.0013

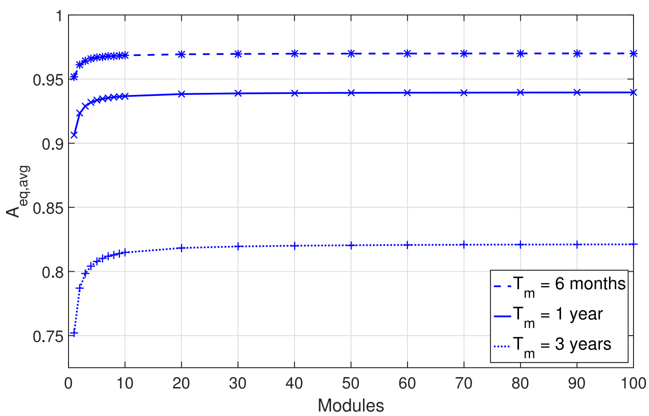

Fig. 11. Effect of the number of modules on the effective availability averaged over one maintenance period for different maintenance periods and $\lambda = 0.2$ turbine^{-1}year^{-1}.

TABLE III
IMPROVEMENT IN AVAILABILITY FOR EXTENSIVE MODULARITY (WRT T_m)

$\lambda = 0.2$			
Failure Rate T_m	$A_{N=20}$	ΔA_{eq}	$A_{N=100}$-$A_{N=20}$
T_m = 6 months	0.9693	0.0182	0.0007
T_m = 1 year	0.9383	0.0331	0.0013
T_m = 3 years	0.8183	0.0692	0.0049

also shows the absolute values for availability with 20 modules. As the probability of the system being in a failed state is strongly proportional to the failure rate (λ), the variation of $A_{N=20}$ with λ is linear as well.

ΔA_{eq} is the net increase in the average equivalent availability ($A_{e,avg}$) when the number of modules are changed from $N = 1$ to $N = 100$.

B. *Effect of Maintenance Periods (T_m)*

The maintenance period (T_m) is an important consideration for the cost of energy of wind turbines. Enforcing periodic scheduled maintenance is a way of reducing maintenance costs. With this constraint, modular design can play a role in increasing the availability of the converter system. Fig. 11 plots the availability over number of modules for three different periodic maintenance strategies.

Again, modularity is more important when the higher periods for maintenance (T_m) are considered. Table III shows the small improvements achieved when increasing the number of modules

TABLE IV
IMPROVEMENT IN AVAILABILITY FOR EXTENSIVE MODULARITY (WRT $\bar{v}$)

T_m = 1 year $\lambda = 0.2$			
Mean Wind Speed $\bar{v}$	$A_{N=20}$	ΔA_{eq}	$A_{N=100}$-$A_{N=20}$
$\bar{v}$ = 8 m/s	0.9539	0.0490	0.0016
$\bar{v}$ = 10 m/s	0.9383	0.0331	0.0013
$\bar{v}$ = 12 m/s	0.9289	0.0234	0.0010

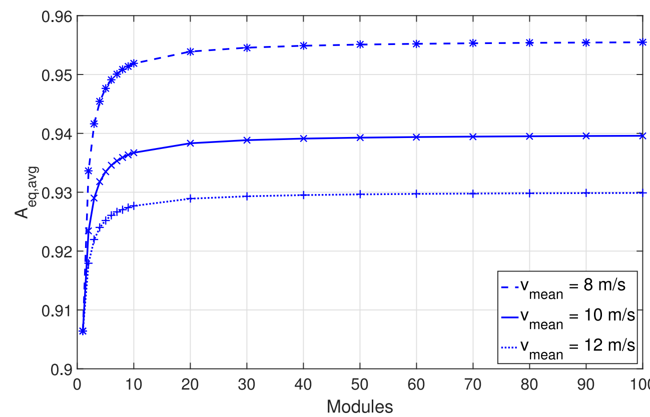

Fig. 12. Effect of the number of modules on the effective availability averaged over one maintenance period for different wind speed profiles with different mean wind speeds. The rated wind speed of the turbine is maintained at 12m/s and $\lambda = 0.2$ turbine^{-1}year^{-1}.

from 20 to 100 for different failure rates. As with the previous case, the variation of $A_{N=20}$ with T_m is almost linear.

C. *Effect of Wind Speed Distribution*

It has been discussed that under partial loading conditions, the modular system of converters can process a larger amount of power with failures (compared to a non modular system). Fig. 7(b) shows that this improvement is dependant on the corner wind velocity (also seen from (7)). Therefore, a wind speed distribution with a concentration on the lower wind speeds will have a higher improvement with the inclusion of modularity. Fig. 12 shows the effect of modularity with three different wind speed distributions.

D. *Discussion on Systems With Periodic Repair*

The study in the previous sections gives rise to a number of properties that are important to consider for the design of such systems.

- An improvement in equivalent availability for modular systems requires some form of over-rating or redundancy. This results in a system that can handle a larger fraction of power than the fraction of modules that are healthy.
- As a significant portion of the operation of a wind turbines is with partial loading, the above requirement is met without the need of either over-rating or additional redundant modules.

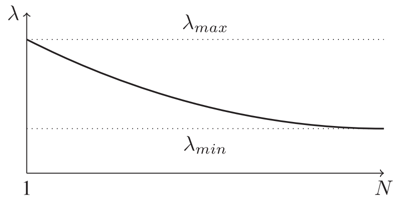

Fig. 13. Failure rates as a continuous function of the extent of modularity.

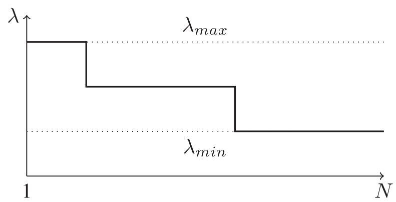

Fig. 14. Failure rates as a step function of the extent of modularity.

- The improvement in equivalent availability reduces with the addition of each additional module. This improvement varies inversely with the number of modules.
- With the number of modules exceeding 10–20, the improvements become such a small fraction of the availability that extreme modularity grants no significant benefit.
- Wind speed distributions with lower mean speeds experience a larger improvement in availability with modularity. This is as such distributions favour partial loading conditions, allowing effective exploitation of modularity.

VI. Systems With Modularity Dependant Failure Rates

The previous analysis considered constant failure rates. This section builds on the analysis by considering failure rates that depend on the extent of modularity. The first case considered, is where the failure rates reduce as a continuous function with the number of modules as shown in Fig. 13. A reason for such a variation could be the reduced power rating of each module as the number of modules is increased. As an example, the failure rate of industrial converters was found to have a lower failure rate (of 0.045 converter^{-1}year^{-1}) when relatively small converters were considered in [3]

Another possibility is that the change in failure rates occur due to a change in technology. Examples of this could be the cooling system where as the power rating of the converter module reduces, the cooling system can be changed from a liquid cooled system to a air cooled system and finally to a passively cooled system. Each of these technology change steps could reduce the failure rates. Another example of this could be the use of PCB based converters when the power rating of the module is small enough which reduces the probability of connection failures. Such a case is shown in Fig. 14.

First, the failure rate is assumed to be a continuous function of the number of modules of the converter system. The analysis considers two curves; a linear, and an exponential function. These are limited between $\lambda = 0.2$ and $\lambda = 0.045$ which are the outer limits for converter failures in the study of wind turbine reliability in [3]. Second, the case of step changes in failure rates is considered. For this illustration, the step is considered at the point when $(N > 50)$. The variation of the considered failure rates are shown in Fig. 15.

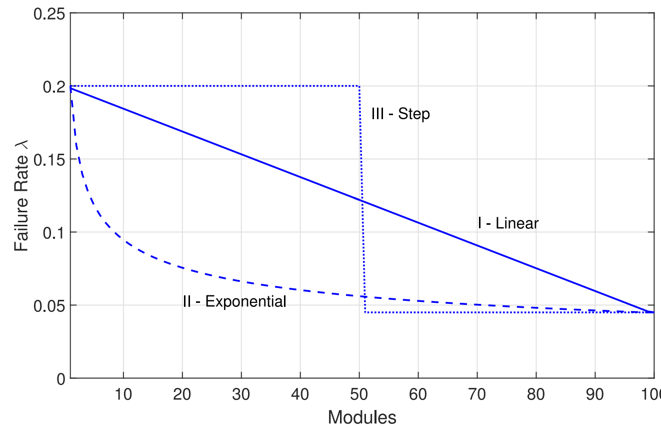

Fig. 15. Failure rate curves.

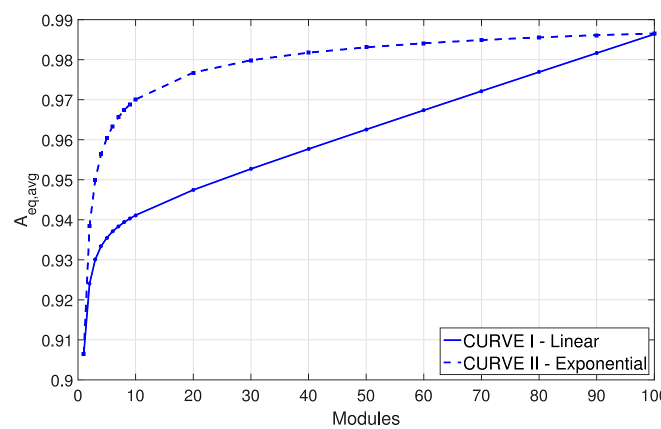

Fig. 16. Equivalent avialability with continuous function failure rates that depend on the number of modules.

Fig. 16 shows the performance of modularity with the linear and exponential variable failure rate curves shown in the Fig. 15. The effect of extreme modularity is now notable. As the failure rate is dependant on the number of modules, and reduces with increasing modularity, the resulting equivalent availability too improves with increasing modularity. The availability curve (Fig. 16) closely follows the failure rate curves ((Fig. 15)).

Fig. 17 shows the availability response to modularity for a system with a step change in failure rates. Here, the change is considered between a failure rate of 0.2 to 0.045 as shown in Fig. 15. turbine^{-1}year^{-1}.

The analysis in this section highlights the following considerations for systems with modularity dependant failure rates,

- The equivalent availability of such a system is strongly dependant on the failure rate curve.
- Extreme modularity is now an option that merits consideration as it can lead to larger improvements in the equivalent availability.

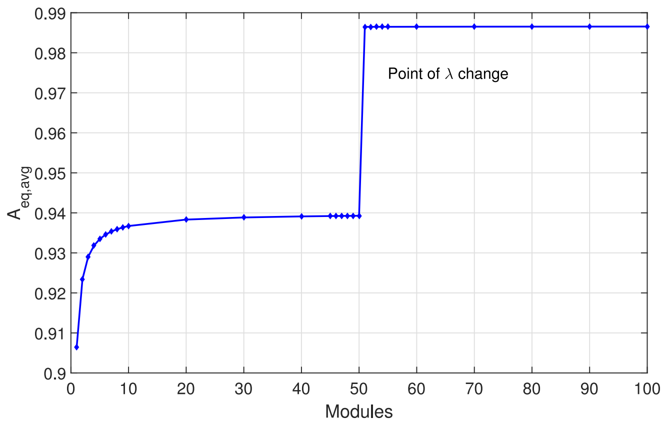

Fig. 17. Equivalent avialability with step function-like failure rates that depend on the number of modules. For this illustrative example, the step is considered at the point when $N > 50$.

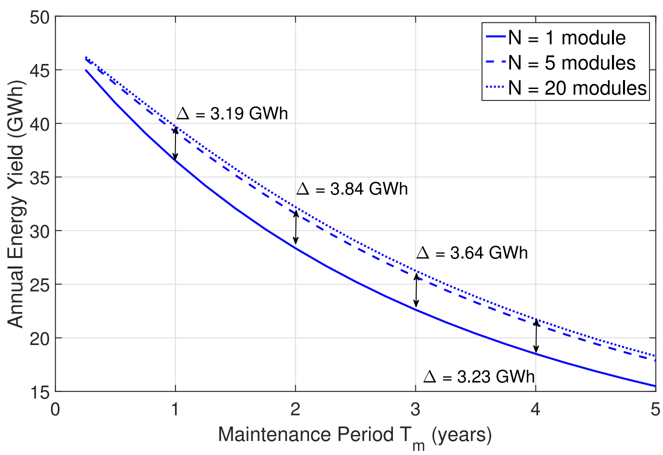

Fig. 18. Annual energy yield for 1, 5, and 20 modules.

VII. Case Study of 10 MW Turbine

In this section, a case study is analysed to quantify the influence of modularity. These case studies only consider periodic scheduled maintenance because such systems are desirable, as they reduce logistic costs of maintenance.

A 10MW wind turbine as designed in [28] with an annual energy yield of 48.4 GWh (for a wind speed distribution with $\bar{v}$= 10 m/s) is utilised for the study. Furthermore, a failure rate of $\lambda = 0.593$ failures turbine^{-1}year^{-1} are considered. This value from [5] is for liquid cooled full scale converters. Fig. 18 plots the annual energy yield for different maintenance periods (T_m) and number of modules (N). In this case the availability of the rest of the turbine is assumed to be 1 and the variations in converter efficiency with modularity is ignored.

It was seen in Fig. 18 that the smaller the maintenance period, the better was the net energy yield, however, there will be a lower limit to this when the cost of maintenance trips and the cost of modularity are considered. Further, from the figure it is evident that modularity can be used to allow an increase in the maintenance period when compared to a case with no modularity. Table V marks the improvement possible in the maintenance period with the use of a converter system with 20 modules, while maintaining the same annual energy yield for the case studied above.

TABLE V
Increased Maintenance Periods With Constant Annual Energy Yield

	Maintenance Period T_m (years)		
Annual Yield (GWh)	1 module	20 modules	Gain
45	0.24	0.39	62.5%
40	0.67	0.96	43.3%
35	1.16	1.60	37.9%

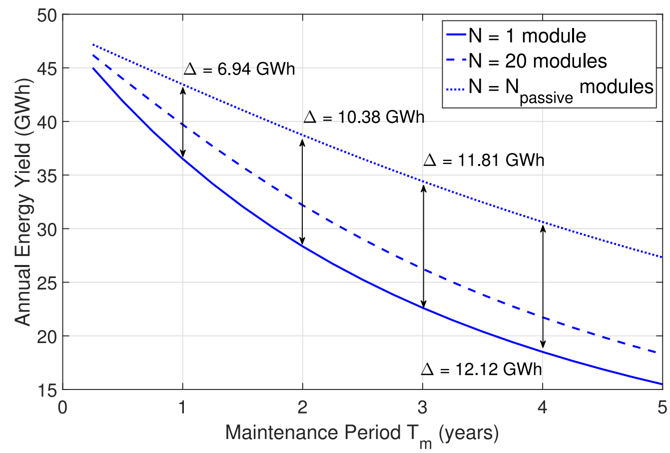

Fig. 19. Annual energy yield with extreme modularity.

TABLE VI
Increased Maintenance Periods With Constant Annual Energy Yield With the Inclusion of Extreme Modularity

	Maintenance Period T_m (years)		
Annual Yield (GWh)	1 module	N_{passive} modules	Gain
45	0.24	0.68	183.3%
40	0.67	1.72	156.7%
35	1.16	2.86	145.9%

According to the study in [5], approximately 44% of the failures in the fully rated converters are due to the cooling system. With the introduction of extreme modularity, it is possible to implement thermal management for the converter using passive cooling. It can be hypothesised that this change would result in a reduction of the failure rate by approximately 44% as it eliminates a failure mode. A comparison of the annual energy yield when the number of modules are sufficient to allow passive cooling ($N = N_{\text{passive}}$) is presented in Fig. 19.

Furthermore, the possible increase in the maintenance period with the use of a converter system with N_{passive} modules, while maintaining the same annual energy yield for the case studied above is presented in Table VI. The results show that extreme modularity, if it brings about a reduction in failure rates, can have a significant impact on the cost of energy.

The use of modular converters also have a number of consequences that are difficult to quantify for the range of modularity considered in this paper. One such example is the cost of converters, which is affected by a large number of factors that can vary with the number of modules considered. These aspects are briefly addressed here:

- Harmonics — parallel modular converters can be used to eliminate PWM-harmonics [29]. This can result in reduced filter sizing [30], [31].
- Efficiency — this also gives rise to the possibility of choosing converters to operate close to rated power, thereby increasing efficiency [29]. Efficiency improvement can also be achieved when modularity allows a transition in the technology used. An example of this is depicted in [32] for a DC-DC converter, where an increase in modules allows a transition from IGBT to MOSFETS leading to an increase in the efficiency.
- Cost — this is a factor that is difficult to accurately estimate across the large range of modules considered in this paper. Increased modularity generally results in an increase in costs. However, some consequences of modularity can reduce this cost burden. For example, the reduced filter sizing as well as a transition in technology as illustrated above can reduce the magnitude of the cost burden. Finally, increased modularity can also cause changes in manufacturing techniques (for example going from hand assembly to automation) which also has a bearing on the final cost of the converters.

VIII. Conclusions

This paper has investigated the use of extreme modularity in a wind turbine converter system from the point of view of its availability. Based on the analysis a number of conclusions have been drawn for systems with failure rates that are constant and independent of module rating:

- For systems with continuous repair, modularity does not improve availability. In fact, modularity would increase the cost of repair as it would involve a higher number of maintenance visits.
- For systems with periodic repair, improvement in availability comes with some form of over-rating and modularity.
- As wind turbine systems often run at partial loading conditions, they are well suited to take advantage of this to improve availability without the need for either over-rating or redundancy.
- The improvement in availability reduces with each increment in the number of modules. The improvement after the number of modules exceeds 10–20 becomes insignificant.
- Therefore, extreme modularity does not offer any benefits when the failure rates are constant.

Futher, the paper analysed systems where the failure rates are dependant on the extent of modularity. This analysis concludes that:

- Extreme modularity may now be a viable option as it can lead to a reduction in failure rates and hence an improvement in the availability of the system.

In conclusion, extreme modularity for converter systems where failure rates are constant do not hold merit as they do not offer significant improvements in availability. However, if the failure rates can be reduced by introducing extreme modularity, the increase in availability can be significant. Therefore, extreme modularity can be a powerful tool, but only when it is accompanied by a reduction in failure rates.

Appendix

The power fraction vector gives the ratio of power produced in a $State - k$ to the power produced with no failures (or $State - 0$). As discussed in Section V, a modular wind turbine can produce power as per the origional power curve upto a corner wind speed v_c and uses a derated power for larger wind speeds. Therefore, the power fraction vector is defined by (6) where P_g is the power curve of the generator system as a function of wind velocity, P_l is the power curve when $v_{\text{corner}} < v < v_{\text{rated}}$, $f(v, a, b)$ is the Weibull probability function with parameters a and b and are given in (9).

$$\begin{aligned} P_g(v) &= P_r \cdot \left(\frac{v}{v_r}\right)^3 \\ P_l(v) &= P_g(v_c) + \frac{P_g(v_r) - P_g(v_c)}{v_r - v_c} \cdot v \\ f(v, a, b) &= \frac{a}{b} \cdot \left(\frac{v}{b}\right)^{a-1} \cdot \exp\left(-\left(\frac{v}{b}\right)^a\right) \end{aligned} \tag{9}$$

where P_r and v_r are rated power and wind speed. Therefore,

$$g_1(v_c, a, b) = \int_0^{v_c} P_r \cdot \left(\frac{v}{v_r}\right)^3 \cdot \frac{a}{b} \cdot \left(\frac{v}{b}\right)^{a-1} \cdot \exp\left(-\left(\frac{v}{b}\right)^a\right) dv$$

using $x = (v/b)^a$ resulting in $dx = (a/b) \cdot (v/b)^{a-1}$, this simplifies to,

$$g_1(v_c, a, b) = \int_0^{(\frac{v_c}{b})^a} \frac{P_r \cdot b^3}{v_r^3} \cdot x^{\frac{3}{a}} \cdot \exp(-x)\, dx \tag{10}$$

Using integration by parts, this results in,

$$\begin{aligned} g_1(v_c, a, b) = \frac{P_r \cdot b^3}{v_r^3} \cdot \Bigg\{ & \left[-x^{\frac{3}{a}} \cdot \exp(-x)\right]_0^{(\frac{v_c}{b})^a} \\ & + \frac{3}{a} \cdot \int_0^{(\frac{v_c}{b})^a} \exp(-x) \cdot x^{\frac{3}{a}-1}\, dx \Bigg\} \end{aligned} \tag{11}$$

which simplifies to,

$$\begin{aligned} g_1(v_c, a, b) = \frac{P_r \cdot b^3}{v_r^3} \cdot \Bigg\{ & -\left(\frac{v_c}{b}\right)^3 \cdot \exp\left(-\left(\frac{v_c}{b}\right)^a\right) \\ & + \frac{3}{a} \cdot \Gamma\left(\frac{3}{a}\right) \cdot \gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right) \Bigg\} \end{aligned} \tag{12}$$

where $\Gamma(x)$ is the Gamma functions, and $\gamma(x, y)$ is the Incomplete Gamma function, given by,

$$\gamma(x, y) = \frac{1}{\Gamma(y)} \int_0^x t^{y-1} \cdot \exp(-t)\, dt \tag{13}$$

Similarly, g_2, and g_3 simplify to,

$$g_2 = \frac{N-k}{N}\frac{P_r}{v_r}\left\{v_c \exp\left(-\left(\frac{v_c}{b}\right)^a\right) - v_r \exp\left(-\left(\frac{v_r}{b}\right)^a\right)\right\}\cdots$$
$$+ \frac{N-k}{k}\frac{P_r b}{v_r a}\Gamma\left(\frac{1}{a}\right)$$
$$\times\left\{\gamma\left(\left(\frac{v_r}{b}\right)^a, \frac{1}{a}\right) - \gamma\left(\left(\frac{v_c}{b}\right)^a, \frac{1}{a}\right)\right\}$$
$$g_3 = \frac{N-k}{N}\cdot P_r \cdot \exp\left(\left(\frac{v_r}{b}\right)^a\right). \tag{14}$$

The addition of these functions, g_1, g_2, and g_3, results in,

$$g = \left(\frac{b}{v_r}\right)^3\left\{\frac{3}{a}\Gamma\left(\frac{3}{a}\right)\gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right)\right\} + \frac{N-k}{N}$$
$$\cdot\frac{b}{v_r a}\Gamma\left(\frac{1}{a}\right)\left\{\gamma\left(\left(\frac{v_r}{b}\right)^a, \frac{3}{a}\right) - \gamma\left(\left(\frac{v}{b}\right)^a, \frac{3}{a}\right)\right)\right\}. \tag{15}$$

When the power fraction vector is put together, it can be seen that it is independent of P_r but a function of a, b, k, and N.

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